Report 332

Ground-Water Resources of the Carrizo-Wilcox Aquifer in the Central Texas Region

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Texas Water Development Board

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The study area of the CarrizoWilcox aquifer in the central Texas region, covers approximately 6,000 square miles. It extends in a southwest direction from the Trinity River to the San Marcos River and covers all or parts of Bastrop, Brazos, Burleson, Caldwell, Falls, Fayette, Freestone, Gonzales, Grimes, Lee, Leon, Limestone, Madison, Milam, Navarro, Robertson, and Williamson Counties.

The hydrologically connected Carrizo Formation and Wilcox Group regionally form the Carrizo-Wilcox aquifer. Collectively the units, composed dominantly of sand and shale, represent extensive ancient deposition in a river and delta complex. The Wilcox Group can be further subdivided in areas northeast of the Colorado River into the Calvert Bluff, Simsboro, and Hooper Formations. The Carrizo and Simsboro sands are the most significant water-bearing units.

Recharge to the Carrizo-Wilcox aquifer enters the aquifer primarily through infiltration in the outcrop from rainfall and from streams which cross its outcrop. Since the aquifer is nearly full, a substantial amount of recharge is rejected in the outcrop and only a small amount moves downdip. Additionally, a considerable amount of in terformational leakage from overlying younger beds is occurring. With increased pumpage, both annual effective recharge to the outcrop and interformational leakage can be increased. Model-derived data on the north one-half of the study area suggest that slightly less than 3 percent of the mean annual rainfall over the outcrop goes to effective recharge. With increased pumpage under controlled conditions, effective recharge can be increased to about 5 percent.

All water-bearing units of the Carrizo-Wilcox aquifer contain fresh to slightly saline ground water. Well yields from the formations range from less than 100 to greater than 2,500 gallons per minute (gal/min) with the largest yields available from the Carrizo and Simsboro Formations. More than 90 percent of wells included in this study produce water with less than 1,000 milligrams per liter (mg/l) dissolved solids suitable for most purposes with little or no treatment. Excessive iron content is, locally, the main water quality problem associated with Carrizo-Wilcox water. Water from the aquifer is suitable for irrigation, but is generally used only as a supplement during times of deficient rainfall.

About 40,800 acre-feet of ground water was used within the study area for all purposes during 1980. Of this amount, approximately 83 percent was used for public supply, 8 percent for rural domestic and livestock needs, 5 percent for irrigation, and 4 percent for industrial purposes. Because of the small amount of ground-water consumption, water-level declines have been restricted to small isolated areas of pumpage; in many wells, water levels have remained steady or periodically risen.

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INTRODUCTION

Location and Population

The study area for this investigation of the Carrizo-Wilcox aquifer in the central Texas region is a long narrow band bordered by the Trinity River to the northeast and the San Marcos River to the southwest. It includes the outcrop of the Carrizo-Wilcox aquifer and the area southeast of its outcrop in which the aquifer contains fresh to slightly saline water in the subsurface. This region is located in the Brazos, Colorado, Guadalupe, and Trinity River basins and covers approximately 6,000 square miles. This study covers all or parts of Bastrop, Brazos, Burleson, Caldwell, Falls, Fayette, Freestone, Gonzales, Grimes, Lee, Leon, Limestone, Madison, Milam, Navarro, Robertson, and Williamson Counties (Figure 1). Data obtained from the 1980-81 Texas Almanac indicate a 1977 census population of approximately 220,000 for this area, which is about 1.7 percent of the total population of the State. Data were also collected in several counties outside of the study area (Anderson, Houston, Lavaca, Walker, and Washington Counties) to aid in making maps to be used in the construction of a computer simulation model of the Carrizo-Wilcox aquifer.

Purpose and Scope

The primary purposes of this study were: 1) to determine the occurrence, availability, and quality of ground water within the Carrizo-Wilcox aquifer in the central Texas region; and 2) to construct a three-dimensional computer model which would simulate ground-water movement within the Carrizo-Wilcox aquifer and then predict its response to future projected pumping conditions.

The general scope of this study was: a) to organize and evaluate, on a regional basis, previously compiled geologic and hydrologic data; b) to collect and tabulate any additional pertinent data, and incorporate them into the existing database; c) to construct interpretative cross sections and maps which demonstrate the regional geologic and hydrologic character of the aquifer; d) to determine the hydrologic parameters (transmissivity, hydraulic conductivity, and storage) and water-quality variations within the aquifer; e) to conduct a test-well drilling program which included coring, borehole geophysical logging, and water sampling from specific depth intervals; f) to evaluate results of the computer simulation; and g) to identify any present and potential ground-water quality problems within the study area.

This report summarizes the geohydrologic phase of this investigation and contains information on the Carrizo-Wilcox aquifer's hydrologic characteristics, the chemical quality of its water, and refined water-availability data for the aquifer between the Trinity and Brazos Rivers. The water-bearing strata of the Carrizo-Wilcox aquifer are also discussed. A subsequent report will include documentation for and results of runs from two modular three-dimensional finite-difference ground-water flow models which simulate ground-water conditions from the Trinity to the Colorado River.

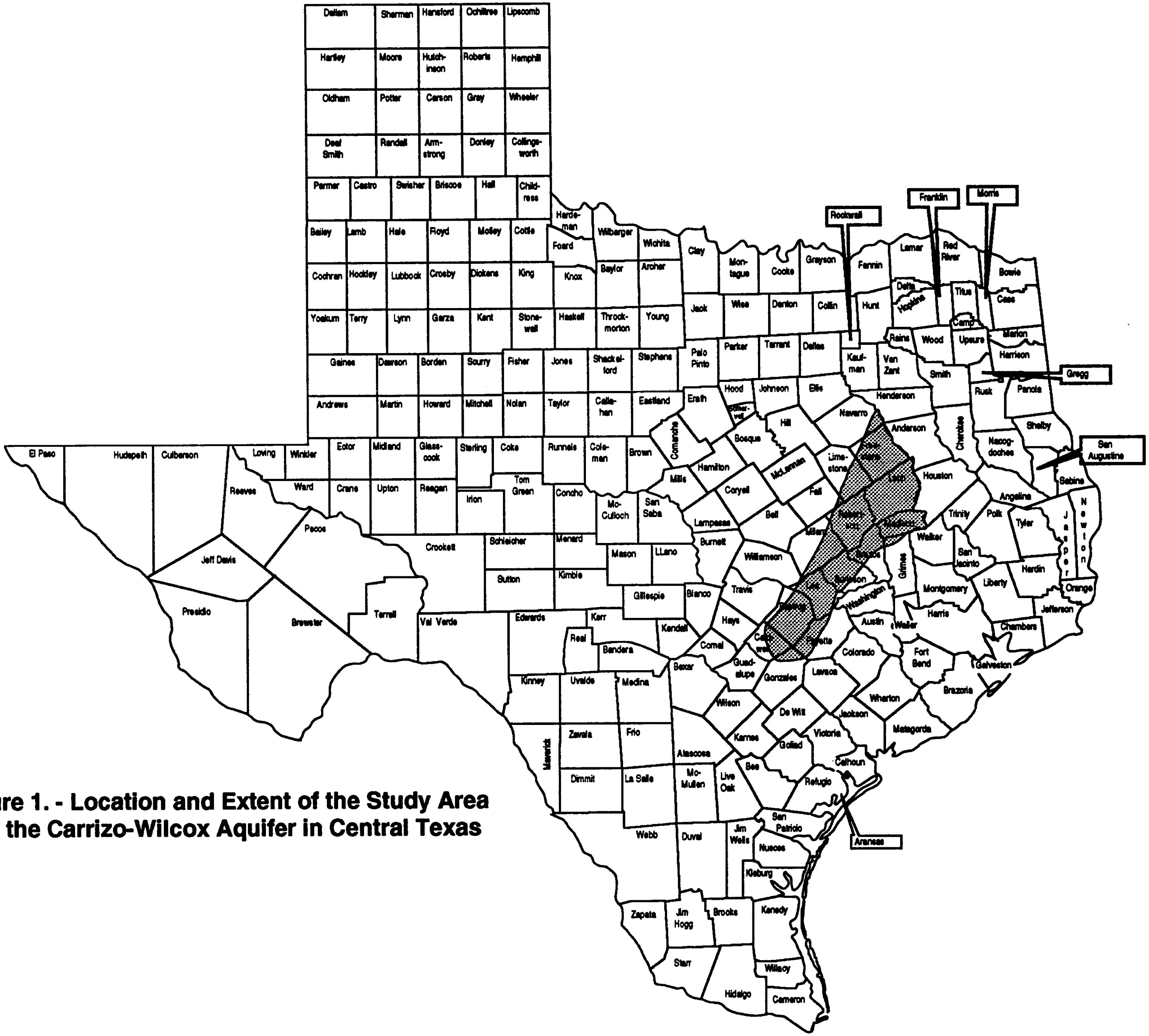


Figure 1. - Location and Extent of the Study Area for the Carrizo-Wilcox Aquifer in Central Texas

Climate

The climate of the study area is generally subhumid to humid and is characterized by long summers and relatively short winters. Average monthly temperature for the period 1951-80 range from a low of 34 degrees Fahrenheit (°F) during January to a high of 97°F during July. The average annual temperature for the same period ranged from 66°F in the northeast portion of the study area to 69°F in the southwest portion (Larkin and Bomar, 1983). Average annual precipitation ranges from 42 inches in the northeast to 33 inches in the southwest, yielding a regional average precipitation of 38 inches. These figures are based on measurements made at selected National Weather Service monitor stations covering the period 1900 through 1980 (Figure 2). The average annual gross lake-surface evaporation for the period 1950 through 1979 ranged from 61 inches along the northwest margin of the study area to 51 inches in the northeast (Larkin and Bomar, 1983).

Economy

The economy of this region is based on agribusiness, manufacturing, and oil and gas exploration and production. Agribusiness, which makes up an important part of the economic structure in every county, consists primarily of raising beef and dairy cattle, hogs, and poultry along with growing the principal crops of corn, cotton, grain, sorghum, wheat, oats, and vegetables. Other supplementary crops include pecans, peanuts, soybeans, watermelons, peaches, and berries (Dallas Morning News, 1979).

In addition to agribusiness, production of a variety of manufactured goods contributes significantly to the overall economy. Several of these are cottonseed oil, clay and clay products, brick, lumber, furniture, sand, gravel, and clothing (Dallas Morning News, 1939).

Oil and gas exploration and production is active throughout the region. Caldwell County averages 18 million dollars worth of income annually from the production of oil and gas, while Limestone and Lee Counties average 14 and 9.9 million dollars, respectively (Dallas Morning News, 19'79). The increased demand for less traditional forms of energy has also led to extensive lignite exploration. The Wilcox Group of this area contains some of the largest commercial lignite deposits in Texas. Active mining is taking place in Bastrop and Milam Counties with a forecasted development to take place in Limestone, Freestone, Lee, and Leon Counties.

Methods of Investigation

The first objective of this study was to organize and evaluate all previously compiled geologic and hydrologic data dealing with the Carrizo-Wilcox aquifer in the central Texas region. Field work consisted of revisiting selected, previously inventoried wells and making an inventory of several new wells in areas where data were lacking. If possible, water levels at each location were measured; at selected locations, water samples were collected for chemical analysis. The Texas Department of Health laboratory performed the analyses on the water samples.

A test hole drilling program was conducted with a total of seven holes being drilled at selected locations in the region. Drill cores were taken and a complete suite of geophysical logs was run for each test. Additionally, all test holes were converted into observation wells and equipped with recorders to continually monitor water-level fluctuations in response to seasonalvariation in precipitation and pumpage. A network of supplementary observation wells was also set up near each test hole to measure water levels on a monthly basis.

One of the most significant aspects of this study was the construction of a computer model for simulations of the aquifer using measurements and estimates of the necessary hydrologic and geologic parameters. These simulations will be used as planning tools for predicting future regional ground-water conditions based upon projected water demands.

The finite-difference computer model used for the simulation of flows in the Carrizo-Wilcox aquifer was developed by Michael G. McDonald and Arlen W. Harbaugh of the U.S. Geological Survey (McDonald and Harbaugh, 1984), and contains some modifications for data input by Dr. Tommy Knowles.

Personnel

The authors began work on this project during 1981. During the investigation period, the study was under the general direction of Tommy Knowles, Director of Planning; Henry Alvarez, Chief, Ground Water Section; and Richard Preston, Geologist with the Ground Water Section.

Gail Duffin, James Sansom, and the authors participated in the test hole drilling program with the actual drilling and laboratory analysis of core samples being performed by the Board's Material Testing Laboratory under the direction of Marion Striegler.

In the early stages of the project, some preliminary work and well inventory were performed out of the Board's San Antonio office with Glen Elder in charge. Additional supplemental well inventory and maintenance of water-level observation wells were completed by Gerald Adair and John Derton, also of the Board's staff.

Acknowledgments

The authors wish to extend acknowledgement and thanks to the property owners throughout the study area who supplied information concerning their wells and, in many cases, allowed access to their property for the purpose of data collection. Acknowledgement is also extended to the various city officials, water superintendents, officials of independent water companies, and local drillers whose information and participation were an invaluable aid in the completion of this study. The cooperation received from federal and other State agencies, especially the State Department of Highways and Public transportation, is also acknowledged and appreciated.

Special thanks are extended to Mr. D.A. McCrary of Calvert and Mr. W.T. Higgins, Jr. of Bastrop. These men allowed the use of their property which enabled the Board to drill and complete permanent observation wells used to monitor water-level fluctuations in response to seasonal changes.

GEOLOGY AS RELATED TO THE OCCURRENCE OF GROUND WATER

Regional Stratigraphy and Structure

The principal water-bearing unit within the study area is the Carrizo-Wilcox aquifer. It consists of the Carrizo Formation and the Wilcox Group, each of Tertiary age, with the Carrizo Formation being the younger of the two and unconformably overlying the Wilcox Group. In most of the central Texas region, the Wilcox Group is divided into three formations. From oldest to youngest they are the Hooper, Simsboro, and Calvert Bluff Formations. This division cannot be made south of the Colorado River or north of the Trinity River due to the absence of the Simsboro Formation as a distinct unit, which is the result of the complex distribution of depositional systems that formed the Wilcox Group. The term "Wilcox Group undifferentiated" is used in this report in areas south of the Colorado River and north of the Trinity River, or where data are insufficient to make a more refined aquifer assignment.

As previously mentioned, Wilcox Group sediments were deposited by more than one depositional system. In central Texas, these systems combined to form an extensive river and delta depositional complex (Kaiser, 1978). Over time, this complex enlarged toward the southeast and transported large quantities of sediment into the ancestral Gulf Coast basin which, along with other major structural features in east and central Texas, is shown in Figure 3. This large influx of material caused subsidence of the basin and thus allowed for the accumulation of a very thick sequence of Wilcox Group sedimentary rocks (Fisher and McGowen, 1967).

There are different opinions concerning the depositional environment of the Carrizo Formation. Geologists have postulated a range of ideas concerning the origin of this unit and have classified it anywhere from continental and fluvial to completely beach and nearshore marine in nature. It is probable that some combination of fluvial and nearshore marine processes are responsible for Carrizo deposition.

The outcrops of the Carrizo Formation and Wilcox Group between the Trinity and San Marcos Rivers form a band 10 to 26 miles in width which trends northeast (Figure 10). Southeast of the outcrop, individual beds dip into the subsurface at rates which range from less than 100 feet per mile in shallow updip areas to more than 200 feet per mile in the deeper downdip areas. Total thickness of the Carrizo Formation is generally 300 feet or less, but it can be in excess of 800 feet, while the Wilcox Group can attain a cumulative thickness of greater than 3,000 feet. Figures 19 through 23 are geologic cross-sections which provide a generalized two-dimensional view of the Carrizo-Wilcox aquifer at various locations in the study area. These sections illustrate regional correlations of the different formations, their structural attitudes, and variations in thickness. Ground-water flow in the subsurface follows the direction of decreasing head or pressure which is

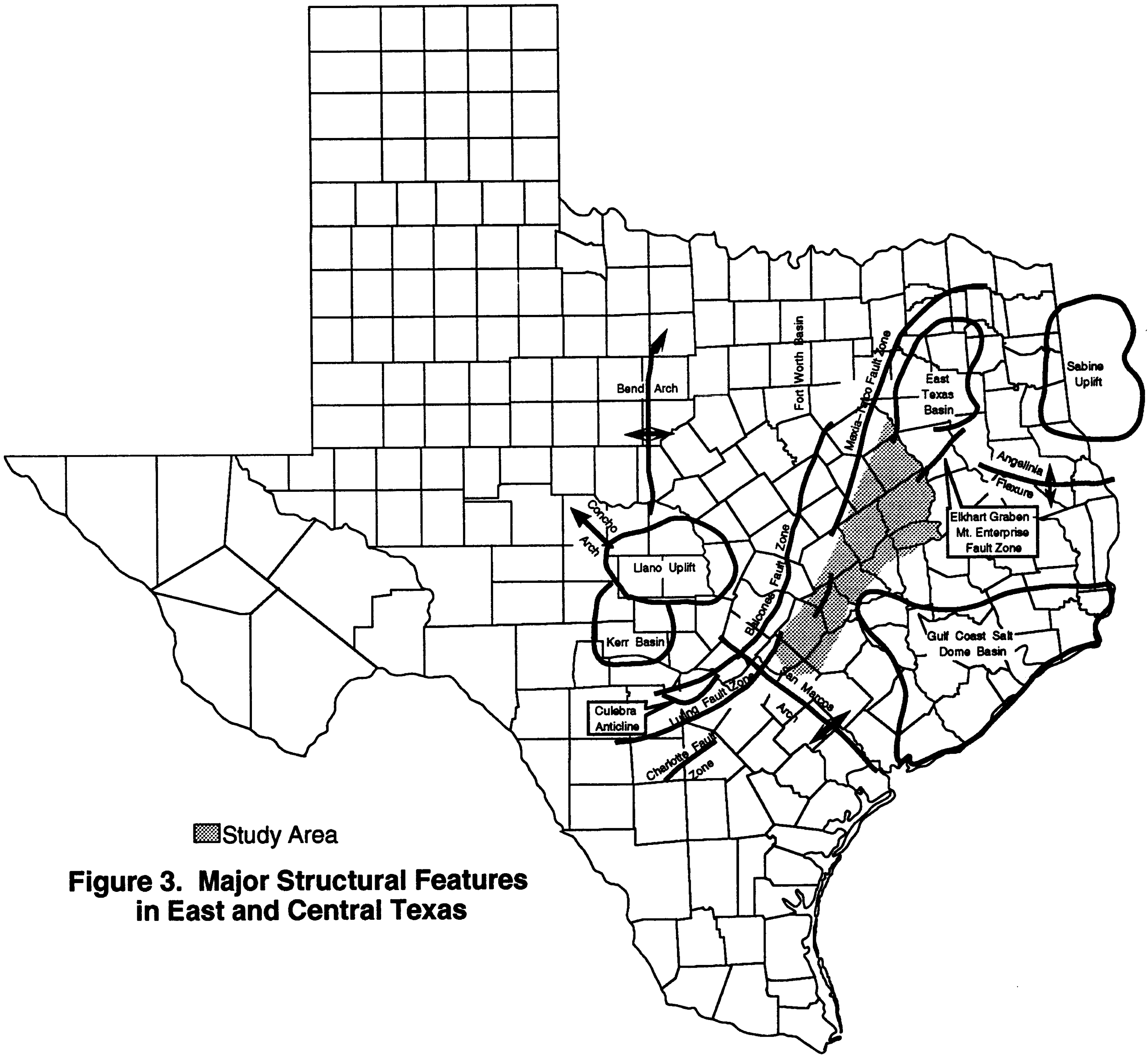


Figure 3. Major Structural Features in East and Central Texas

generally in the direction of regional dip; however, the presence of areas of heavy pumpage, extensive faulting, or structures such as salt domes may alter local flow patterns.

Principal Water-Bearing Units

Formations of the Claiborne and Wilcox Groups form the principal water-bearing units in the central Texas region. The Carrizo Formation of the lower Claiborne Group unconformably overlies the Calvert Bluff, Simsboro, and Hooper Formations of the Wilcox Group. Hydrologic continuity often exists between sands of the Carrizo and Calvert Bluff Formations, therefore the term "Carrizo-Wilcox aquifer" is used when referring to the entire sequence. A summary of these units, which includes the character of the rocks and their water-bearing properties, is given in Table 1. Regionally, the largest volume of ground water is obtained from the Carrizo and Simsboro Formations of the Carrizo-Wilcox aquifer. They also have the greatest potential for future development.

Wilcox Group

Wilcox Group sediments, in most of the study area, were deposited by a fluvial-deltaic system and consist mainly of fine- to coarse-grained sand with interbedded clay of varying proportions throughout the section. Total thicknesses reach a maximum in excess of 3,000 feet. Between the Colorado and Trinity Rivers, the Wilcox Group is divided into the three previously mentioned formations which form the dominant water-bearing units of the aquifer in the region. Figure 11 depicts the approximate net sand containing fresh to slightly saline water in the Wilcox Group sediments within the study area. Saturated sands reach a maximum thickness of 2,400 feet in Madison County, just north of Madisonville.

South of the Colorado River and north of the Trinity River the character of the Wilcox changes significantly. Simsboro Formation sands no longer form a distinct unit and the three formational divisions cannot be made. North of the Trinity River, Wilcox deposition was dominantly fluvial in nature and the sediments are generally fine- to medium-grained, cross-stratified sand interbedded with clay, sandy clay, and thin beds of lignite. South of the Colorado River, Wilcox sediments are lithogically similar to those farther north; however, they were influenced by nearshore marine processes and are characterized by interbedded limestone lenses and marine clays. In this southern part of the study area the Wilcox continues to be a source of ground water, but regionally the Carrizo Formation becomes the principal aquifer.

Hooper Formation

Hooper Formation sediments comprise the basal portion of the Wilcox Group and conformably overlie marine muds of the Midway Group. Lithologically, the Hooper consists predominantly of mudstone with various amounts of light gray to medium brown, fine- to medium-grained sandstone. Other minor constituents include ironstone concretions and thin, discontinuous beds of lignite in the upper part of the formation. In the central Texas region, the gross thickness of the Hooper can exceed 1,300 feet in the deep subsurface, but generally is less than 500 feet in shallower areas where ground-water development occurs. By comparison, the Hooper is the least productive water-bearing unit in the Wilcox Group with most development taking place on its outcrop (Figure 10) or in relatively shallow

Table 1. - Geologic Units and Their Water-Bearing Properties

<table>
<tr><th>System</th><th>Series</th><th>Group</th><th colspan="2">Geologic Unit</th><th colspan="2">Approximate Maximum Thickness (feet)</th><th colspan="2">Character of Rock</th><th colspan="2">Water-Bearing Properties</th></tr>
<tr><td rowspan="4">Tertiary</td><td rowspan="4">Eocene</td><td>Claiborne</td><td colspan="2">Carrizo Formation</td><td colspan="2">880</td><td colspan="2">Fine to coarse sand. Light to dark gray, massive, commonly cross-bedded with some thin beds of sandstone and clay.</td><td colspan="2">Yields small to large quantities of fresh to slightly saline water.</td></tr>
<tr><td rowspan="3">Wilcox</td><td rowspan="3">Wilcox Undifferentiated</td><td>Calvert Bluff Formation</td><td rowspan="3">3,430</td><td>2,130</td><td rowspan="3">Fine to medium sand and sandstone. Light gray to moderate brown, commonly cross-bedded, lenticular, and interbedded with clay, sandy clay, some lenses of limestone, and thin beds of lignite. Wilcox Undifferentiated is a term generally used in referring to that part of the Wilcox group south of the Colorado River and north of the Trinity River. However, in this report, the same term is applied to those sediments between the Trinity and Colorado Rivers where data is not sufficient to make a more refined aquifer assignment.</td><td>Fine to coarse lenticular sand and sandstone. Light gray to pale brown, cross-bedded, and argillaceous in some areas, interbedded with various amounts of mudstone, ironstone concretions, and discontinuous beds of lignite.</td><td rowspan="3">Yields small to large quantities of fresh to slightly saline water.</td><td>Yields small to moderate quantities of fresh to slightly saline water.</td></tr>
<tr><td>Simsboro Formation</td><td>880</td><td>Fine to coarse light gray sand composed dominantly of quartz. Sand is massive and cross-bedded, containing relatively small amounts of clay, mudstone, and mudstone conglomerate.</td><td>Yields small to large quantities of fresh to slightly saline water.</td></tr>
<tr><td>Hooper Formation</td><td>1,380</td><td>Dominantly mudstone with various amounts of light gray to medium brown sandstone, lignite, and ironstone concretions. Sand-stone is fine to medium grained, cross-bedded, and argillaceous in the lower part of the formation. Lignite forms thin, dis-continuous beds in the upper part of the formation.</td><td>Yields small to moderate quantities of fresh to slightly saline water.</td></tr>
</table>

Yields of wells, in gallons per minute (gal/min): Small = less than 100 gal/min; Moderate = 100 - 1,000 gal/min; Large = More than 1,000 gal/min

Quality of Water, in parts per million (ppm) dissolved solids: Fresh = less than 1,000 ppm; Slightly saline = 1,000 - 3,000 ppm; Moderately saline = 3,000 - 10,000 ppm; Very saline = 10,000 - 35,000 ppm artesian areas. In the Bryan-College Station area, sands of the upper Hooper display electric log patterns similar to those of the overlying Simsboro sediments. This suggests that sedimentary processes which deposited the Simsboro Formation in this area may have begun during late Hooper time. Testing would be necessary to determine whether Hooper well yields and water quality are favorable enough to warrant future development in this locality.

Simsboro Formation

The Simsboro Formation is an identifiable unit only in central Texas, comprising one of the three formational divisions of the Wilcox Group within this region. Sediments of the Simsboro both conformably and unconformably overlie those of the Hooper Formation (Kaiser, 1978). Their composition is primarily of fine- to coarse-grained, light gray sand with relatively small amounts of clay, mudstone, and mudstone conglomerate.

Deposition of the Simsboro occurred in a fluvial environment and formed a complex distribution of sands with diverse sand body geometries. Simsboro sands are discontinuous river channel deposits with interchannel deposits composed of finer-grained sands and muds in the northern portion of the study area, while thick, multilateral sand bodies are found in the southern part (Henry, Basciano, and Duex, 1980). The Simsboro is more equivalent in character to the overlying Calvert Bluff Formation outside of the study area and in its most southerly areas, is actually a nearshore marine deposit (Kaiser, 19’18).

Total thickness, as well as net fresh to slightly saline water-bearing sand thickness (Figure 12), ranges from 0 to more than 800 feet. The Simsboro, is the most dominant hydrologic unit in the Wilcox Group in the central Texas region. Most of the pumpage from the Wilcox Group occurs within the Simsboro, with municipalities such as Bastrop, Bryan, College Station, and Elgin obtaining most of their water from this unit. As in the Hooper Formation, development occurs mainly on the Simsboro outcrop (Figure 10) or in shallow artesian areas; however, some of the most productive Simsboro wells are completed at depths in excess of 2,000 feet. Figure 13 is a structural map showing the altitude of the top of the Simsboro Formation. It also shows the rate of dip, regional variation in depth, and structural complexity of this unit.

As an aquifer, the Simsboro has excellent possibilities for future development. Its sandy, permeable nature makes it an excellent conduit for ground water, and thick accumulations create areas of high potential yield.

Calvert Bluff Formation

The Calvert Bluff Formation is the youngest of the three units which make up the Wilcox Group. It lies conformably above the sands of the Simsboro Formation and represents a period of fluvial and deltaic deposition during late Wilcox time (Kaiser, 19’78). Lithologically, the Calvert Bluff consists of fine- to coarse-grained, light gray to pale brown sand and sandstone interbedded with various amounts of mudstone, ironstone concretions, and discontinuous beds of lignite. Total thickness ranges from 0 to more than 2,000 feet. Sand deposits are lenticular and commonly cross-stratified, resulting from deposition in extensive fluvialdeltaic channel complexes.

Between channel sands, interchannel fine-grained sand and mud deposits occur. During Wilcox time when this depositional system was active, large amounts of organic material also accumulated in the interchannel areas, and these eventually formed modern day lignite deposits. Some of these are now being mined within the study region.

Ground-water development in the Calvert Bluff Formation is similar to that of other Wilcox Group units, taking place primarily in the Calvert Bluff outcrop and shallow artesian areas. However, the potential for more extensive utilization seems favorable. Calvert Bluff channel sands are often lithologically similar to Simsboro sand bodies and probably have similar hydrologic properties (Henry, Basciano, and Duex, 1980). Therefore, in areas where such sands are relatively widespread and have adequate thickness, this aquifer could prove to be a viable future resource.

Carrizo For5mation of the Claiborne Group

Carrizo Formation sediments form the basal unit of the Claiborne Group in Texas and lie unconformably above the Calvert Bluff Formation of the Wilcox Group. There is some disagreement in the literature concerning the environment in which Carrizo deposition took place. Henry and Basciano (19’79) and Fogg and Kreitler (1982) believe the Carrizo to be primarily a continental and fluvial deposit while Payne (19’75) considers the Carrizo to have a beach and nearshore marine origin. Todd and Folk (195’7) postulate that early Carrizo deposition was indeed fluvial in nature while nearshore brackish-water processes controlled deposition during late Carrizo time.

Lithologically, the Carrizo is composed predominantly of fine- to coarse-grained, light to dark gray sand. Sands are massive and commonly cross-stratified with only minor beds of sandstone and clay. Unlike the lentitular localized sands of the Wilcox Group, Carrizo sands form a thick, continuous sheet-type deposit that extends regionwide. Figure 14 is a structure map which shows the altitude of the top of the Carrizo Formation. It illustrates variations in depth and the structural effects of complex zones of faulting. Total thickness and net fresh to slightly saline water-bearing sand thickness (Figure 15) are commonly less than 300 feet; however, in the more southerly portions of the study area, thickness can exceed 800 feet. In these areas, the Carrizo Formation is the principal regional aquifer.

As with the Wilcox Group, ground-water developers of the Carrizo in central Texas do not utilize the full potential of this unit. In many instances, alternative aquifers which are shallower in depth are more economical to tap. This leaves the Carrizo as a significant resource for future development.

GROUND-WATER HYDROLOGY

Source and Occurrence of Ground Water

There are several sources of water to the Carrizo-Wilcox aquifer. A considerable amount is from rainfall on the outcrop and seepage from lakes and streams. Only a small portion of the available water ever reaches the water table. A large amount of precipitation is lost to surface evaporation or becomes runoff to local streams and lakes. Other portions which do infiltrate below the soil are lost by transpiration through plants. There is a small part, however, of the original precipitation which does move slowly downward by gravity and becomes part of the saturated zone. In the Central Texas Carrizo-Wilcox, a significant part of this recharge is lost to spring and seep flow in the outcrop. An additional source, based on model analysis of the area from the Trinity to Brazos Rivers, and the work of others (Thompson, 1966; Fogg and Kreitler, 1982; and Fogg, Seni, and Kreitler, 1982) is from interformational leakage from overlying younger beds. This water replaces some of the water which has been withdrawn from artesian storage due to pumpage.

All ground water occurs under either water-table or artesian conditions. In the Carrizo-Wilcox, water-table conditions exist in the outcrop areas. Here the top of the zone of saturation is under direct atmospheric pressure. Wells in this area are filled with water to the level of the water table, and water levels fluctuate in response to the volume of water in storage. Downdip from the outcrop, where less permeable beds overlie the Carrizo-Wilcox, ground water is under artesian pressure. When this artesian portion of the aquifer is tapped by wells, pressure will cause the water level in the wells to rise above the top of the aquifer and, in many cases, actually flow to the surface. Flowing wells occur most often in areas of low elevation, such as large stream valleys, primarily along the Trinity, Brazos, and Colorado Rivers.

Recharge, Movement, and Discharge

Replenishment of water to the Carrizo-Wilcox aquifer, or recharge, is mainly by natural means. The major source and controlling factor for recharge is the frequency and the amount of precipitation. Other factors include topography, amount and kind of vegetative cover, absorbing characteristics of the soils, and hydraulic conductivity of the rocks involved. Also, seepage from lakes and streams on the aquifer's outcrop and interformational leakage contribute to recharge. Minor amounts of artificial recharge could be accomplished by running water over the aquifer's permeable outcrop or by pumping water into the water-bearing unit through wells. If recharge is less than discharge, over a long period of time, an aquifer will be progressively drained. If recharge is greater than discharge, then water will be taken into storage and will progressively fill the aquifer. The Carrizo-Wilcox aquifer within the study area is nearly full and receives very little recharge. All but a small portion is rejected in the outcrop by means of evaporation, transpiration by plants, and surface runoff to lakes and streams. The natural recharge rate to the Carrizo-Wilcox aquifer is estimated to be slightly in excess of 1 inch per year or 2.69 percent of the mean annual rainfall over the outcrop area based on model runs on the north one-half of the area of investigation. Recharge to the aquifer's outcrop, as well as interformational leakage from overlying younger beds, can be increased by pumpage. Model simulations on the north one-half of the study area indicate that effective outcrop recharge can be increased to about 5 percent of the mean annual rainfall and that leakage from younger formations would exceed outcrop recharge.

The principle direction of initial movement of recharge in the Carrizo Wilcox outcrop is downward through the zone of aeration under the force of gravity. Upon reaching the water table, ground water moves horizontally and in the direction of decreasing head or pressure. This movement is controlled largely by topography in the outcrop area. Flow is generally from topographic highs, which are recharge areas, to topographic lows, which are natural discharge areas. Some ground water moves downdip along the beds of the formation into the artesian section where, due to differences in hydrostatic pressure in the aquifers, it slowly seeps upward through semi-confining beds or along faults into overlying younger units. Rates of movement in the Carrizo-Wilcox are highly variable from one area to another depending on sand body distribution, hydraulic conductivity, and hydraulic gradient. Highest flow rates occur in areas with the largest accumulations of conductive sands. These sands are usually associated with the Carrizo and Simsboro Formations. Estimated flow rates in sands range from a few feet to as much as several hundred feet per year, but are commonly between 10 and 100 feet per year (Thompson, 1966 and Guyton, 19'72). Locally, artificial discharge through pumping wells can alter the direction and rate of the natural flow of ground water.

Discharge is the process by which water is removed from an aquifer. As in the case of recharge, discharge of water from the Carrizo-Wilcox is also by natural and artificial means. Natural discharge occurs as flow to rivers and lakes, discharge from springs, in terformational leakage, transpiration by plants, and by evaporation. In the study area, the Trinity, Brazos, and Colorado Rivers are major sites of natural discharge from the Carrizo Wilcox. Artificially, water is discharged through pumping wells. A summary of major users of ground water from the Carrizo-Wilcox will be discussed in a later section of the text.

Hydraulic Properties of the Aquifer

Hydraulic properties of an aquifer are generally expressed in terms of its coefficients of transmissivity and storage and are controlled by the porosities and hydraulic conductivities of the sediments which make up the aquifer and control its capacity to yield water to wells. The coefficients of transmissivity and storage can be determined through pumping of a test well and the use of repeated measurements of the water levels in the pumping well and nearby observation wells. Since these coefficients are a measure of the aquifer's ability to transmit and store water, they can be used to determine proper well spacing, to determine the effects that a pumping well may have on other wells, and to predict water-level drawdowns at various distances from a pumping well for a specified time and at a given pumping rate. Table 2 summarizes the results of a number of pumping tests performed on the Carrizo-Wilcox aquifer throughout the study area. These results were compiled from data on tests conducted by the Board's staff, the United States Geological Survey, and private businesses and individuals.

Due to the complex lithologic makeup of the Wilcox Group, hydraulic conductivities are highly variable from one area to another. Highest values are found associated with areas where channel sand deposits are present. In these areas, hydraulic conductivities generally range from 20 to 60 feet per day. Lower values are generally found in areas of interchannel sands and muds and commonly range from 3 to 7 feet per day (Henry, Basciano, Duex, 1980). By comparison, the Carrizo Formation is lithologically uniform and has more consistent hydraulic conductivities regionwide, although a large range still exists. Values are similar to those associated with Wilcox channel sands. Payne (1975) states that aquifer tests conducted on the Carrizo sands show that hydraulic conductivities (and, therefore, transmissivities) increase with an increase in the thickness of sand units (Table 2).

To obtain additional aquifer parameters, a test-hole drilling program was conducted. Seven test holes were drilled in five counties using the Texas Water Development Board's drilling rig. Tests were drilled in both the outcrop and downdip areas of the Carrizo-Wilcox aquifer. Cores from these tests holes were analyzed by the Board's Materials Testing Laboratory to obtain information on sand particle diameters and to determine coefficients of grain-size uniformity and hydraulic conductivity (permeability). The results of laboratory determinations for selected parameters from unconsolidated sands of the test holes are summarized in Table 3.

Potential yields to wells are determined by the hydraulic properties discussed above. Yields for wells completed in the Carrizo-Wilcox aquifer range from less than 100 to greater than 2,500 gal/min. This further illustrates the variable nature of this aquifer. Highest yields within the study area are obtained from wells which tap the Carrizo and Simsboro Formations.

The coefficient of storage is the measure of an aquifer's ability to store or release ground water from storage. Storage coefficients in the artesian section generally range from 10^{-2} to 10^{-5} (Table 2) and are smaller than those in water-table areas which have a range from approximately 0.1 to 0.3.

Fluctuations of Water Levels

Ground water in the Carrizo-Wilcox aquifer exists under both water-table and artesian conditions. Water-table conditions occur in the outcrop area, and static water levels in wells there indicate the local position of the water table. Artesian conditions, which occur in most of the study area, exist because the aquifer is overlain by confining beds of lower hydraulic conductivities. This condition produces hydrostatic pressures that 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.

Water-level fluctuations can be regional or local in nature. Small-scale daily fluctuations may be responses to earthquakes, tidal forces, or changes in barometric pressure. Regional fluctuations taking place over longer periods of time, however, result directly from the amount of recharge to and discharge from the aquifer. Seasonal climatic changes play an important role in regional fluctuations—water levels are usually highest in late spring and fall when rainfall is most abundant and lowest in late summer when rainfall is scarce (Figure 4).

Table 2. - Aquifer Yields and Specific Capacities; Coefficients of Storage, Transmissivities, and Hydraulic Conductivities

Aquifer	Discharge Range gal/min	Specific Capacity Range gal/min/ft[1]	Coefficient of Storage, Range [1]	Average Coefficient of Storage [1]	Transmissivity Range, ft^2/d	Average Transmissivity ft^2/d	Hydraulic Conductivity Range, ft/d	Average Hydraulic Conductivity ft/d
Carrizo	11, - 1,650	0.7 - 28.6	0.00016(1)	0.00016(1)	2,425 - 18,027	6,498	26 - 140	75[2]
Hooper	35 - 500	0.5 - 3.5	-	-	112-2,277	543	1-34	7[3]
Simsboro	50 - 2,700	1.3 - 32.0	0.00034 - 0.034	0.0016(6)	147 - 24,452	4,639	2 - 84	24
Calvert Bluff	60 - 445	1.0 - 1.5 (2)	-	-	429 - 2,150	1,289	4 - 18	11
Wilcox (Undifferentiated)	12 - 618	0.5 - 17.7	0.00083 - 0.0012	0.00099(3)	121 - 14,070	3,415	2 - 204	31
Carrizo-Wilcox	391 - 1,105	5.5 - 9.5	0.0000124(1)	0.0000124(1)	1,049-8,710	2,616	7 - 21	12

[1] Numbers in parenthesis indicate the number of tests used to determine the values.
[2] Average hydraulic conductivity is 64 excluding one abnormally high value (140).
[3] Average hydraulic conductivity is 2 excluding one abnormally high value (34).

Table 3.- Summary of Core-Test Analyses

Aquifer	Well Number	Aquifer	Average Sand Grain Diameter 50 Percent Retained (inches)	Average Sorting Coefficient [1]	Average Coefficient of Permeability ($gal/d/ft^2$) [2]	Average Hydraulic Conductivity (ft/d) [2]
Gonzales	KR-67-27-805	Carrizo	.0072	1.48	120 [3]	16
Leon	SA-39-54-604	Carrizo	.0086	1.16	572	77
Limestone	SD-39-37-601	Hooper	.0072	1.55	241	32
Limestone	SD-39-37-601	Simsboro	.0070	1.69	107	14
Milam	TK-59-02-309	Simsboro	.0100	1.31	418	56
Milam	TK-59-11-621	Carrizo	.0080	1.30	349	47

[1] Sorting Coefficient from Trask (1932).
[2] Permeabilities and hydraulic conductivities estimated from sand textures, sieve analyses, and a table derived from the laboratory work of Beard and Wyle (1973).
[3] Represents only finer grained, less permeable zones at this location.

The most significant changes in water levels are the result of heavy pumping. Depending on the reservoir characteristics of an aquifer and the rate of withdrawal, various sizes of cones of depression are formed around the well bores of pumping wells. These cones are formed by the drawdown of the water table or the potentiometric surface and are in the shape of an inverted cone having its apex at the pumped well (Figure 5, Well A). These cones will expand until they encounter a recharge source equal to the discharge rate. If the cone does not encounter a recharge source, it will continue to expand until it encounters the cone of depression of another pumping well, as is the case in highly developed irrigation areas or municipal well fields, and may combine with it and form a large, regional cone of depression in the potentiometric surface or water table (Figure 5, Wells A and B).

Figure 16 is a regional water-level map for the Carrizo-Wilcox aquifer in central Texas. Measurements used to construct this figure were made during 1947 through 1990 with the majority falling between 1965 and 1990. This wide range of years was appropriate because water-level fluctuations for the area were generally small for the time period (Figure 6).

Data for the Carrizo Formation and Wilcox Group water-bearing units were combined on the map because data were insufficient on a regional scale to construct meaningful water-level maps of each individual unit. This was believed to be reasonable because heads in the Carrizo Formation and Wilcox Group show little difference and, therefore, suggest sufficient hydrologic interconnection to allow the entire system to be regarded as one regional flow system. Care should be taken, however, when making applications on anything less than a regional scale since significant differences from local water levels and hydraulic gradients undoubtedly exist.

Available current and historical water-level data for the Carrizo-Wilcox aquifer indicate that water-level declines have been restricted to small isolated areas of pumpage, and in many wells, water levels have remained steady or have risen during recent years.

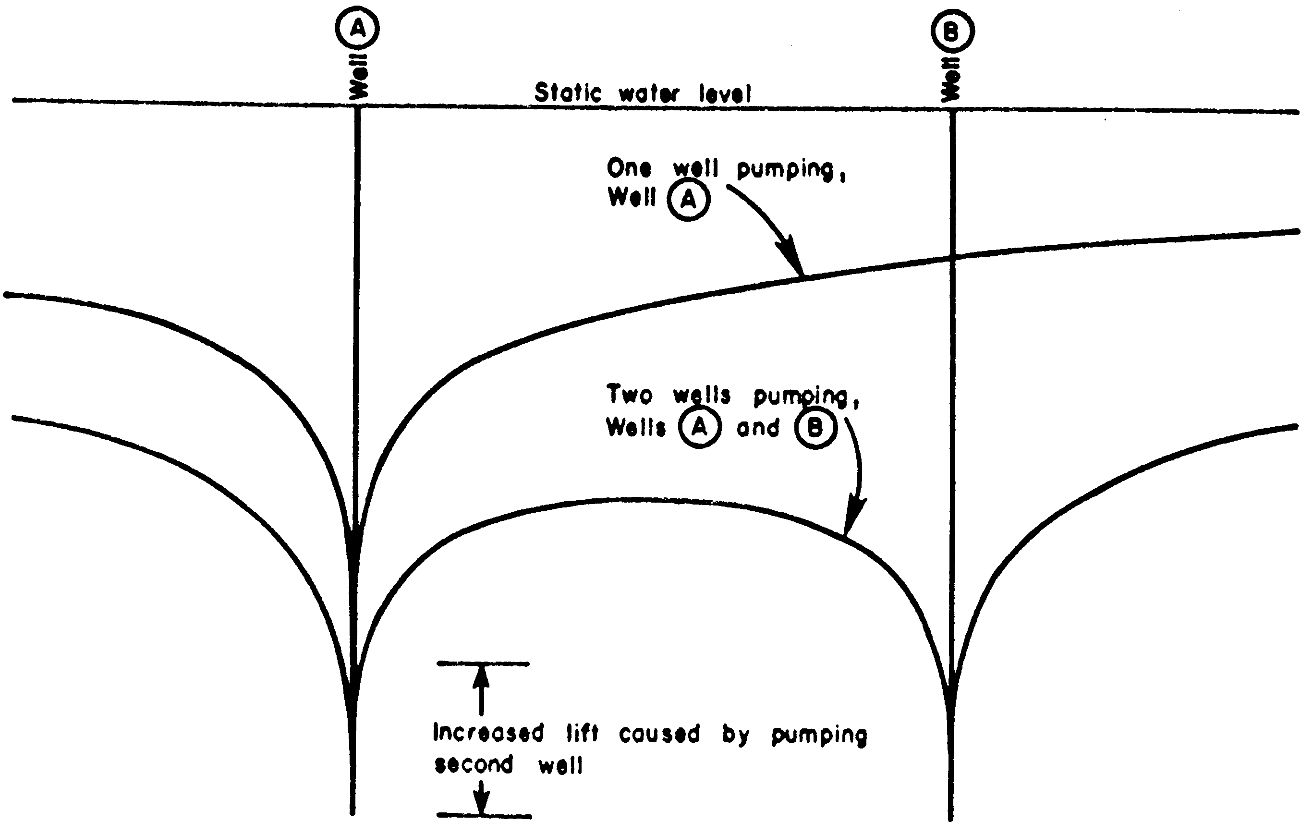


Figure 5 —Idealized Cross Section Showing Drawdown Interference Between Two Pumping Wells

CHEMICAL QUALITY

General Chemical Quality

Both the constituents and concentrations of dissolved minerals carried in ground water are determined mainly by the types of soil and rocks through which the water percolates. The solvent power of water dissolves some of the minerals from the surrounding rocks as water moves through its environment. Concentration of the various dissolved-mineral constituents depends upon the mineral solubility in the water-bearing unit, the length of time the water is in contact with rock, and the concentration of carbon dioxide present within the water. Therefore, the chemical character of ground water mirrors the general mineral composition of the earth through which it has passed. Usually, dissolved-mineral concentrations increase with depth and temperature. The source and significance of dissolved-mineral constituents and properties of water and their range within the individual units of the aquifer within the study area are summarized in Table 4.

Chemical Quality of Ground Water in the Carrizo-Wilcox Aquifer

The Carrizo Formation and the Wilcox Group yield fresh to slightly saline water to almost all of the wells completed in these water-bearing units in the central Texas region. Table 4 shows the range of dissolved-mineral constituents in each of the Carrizo, Calvert Bluff, Simsboro, and Hooper Formations. More than 90 percent of the wells included in this study contain fresh water with less than 1,000 mg/l dissolved solids. The majority of these have less than 500 mg/l. Levels of chloride and sulfate are also low with only 4 percent or less of the analyses showing concentrations in excess of established standards. Figure 17 shows the amounts of chloride, sulfate, and dissolved solids in selected wells completed in the Carrizo-Wilcox aquifer.

Water from the Carrizo-Wilcox is suitable for most purposes with little or no treatment. Numerous municipalities, industries, farms, and households obtain part or all of their water supplies from these units. Since rainfall in central Texas usually provides an adequate water supply for crops, irrigation with ground water is used mainly as a supplement during times when rainfall is deficient. Water from the Carrizo-Wilcox is generally usable for irrigation purposes. The Carrizo and Simsboro Formations are capable of the largest well yields. Figures 7 and 8 classify irrigation waters, by county, for these two formations.

Chemical quality of ground water generally declines with depth throughout the region. This is a result of deeper waters having been in contact with the surrounding formations for longer periods of time. The deeper waters have higher temperatures and are under greater pressures than shallow waters and thus have a higher degree of mineralization.

Figure 18 shows the approximate regional position of the base of slightly saline water within the Carrizo-Wilcox aquifer. This horizon usually corresponds closely to the base of the Wilcox Group in shallow areas. However, in areas where the Wilcox Group lies at greater depths, basal sands commonly contain water with dissolved solids in excess of 3,000 mg/l.

Table 4.--Source, Significance, and Concentrations of Dissolved Mineral Constituents and Properties of Water (Adapted from Doll and others, 1963, p. 39-43)

Constituent or Property	Source or Cause	Significance
Silica (SiO_2)	Dissolved from practically all rocks and soils, commonly less than 30 mg/l. High concentrations, as much as 100 mg/l, generally occur in highly alkaline waters.	Forms hard scale in pipes and boilers. Carried over in steam of high pressure boilers to form deposits on blades of turbines. Inhibits deterioration of zeolite-type softeners.
Iron (Fe)	Dissolved from practically all rocks and soils. May also be derived from iron pipes, pumps, and other equipment.	On exposure to air, iron in ground water oxidizes to reddish-brown precipitate. More than about 0.3 mg/l stain laundry and utensils reddish-brown. Objectionable for food processing, textile processing, beverages, ice manufacture, brewing, and other processes. Texas Department of Health (1988) drinking water standards state that iron should not exceed 0.3 mg/l. Larger quantities cause unpleasant taste and favor growth of iron bacteria.
Calcium (Ca) and Magnesium (Mg)	Dissolved from practically all soils and rocks, but especially from limestone, dolomite, and gypsum. Calcium and magnesium are found in large quantities in some brines. Magnesium is present in large quantities in sea water.	Cause most of the hardness and scale-forming properties of water; soap consuming (see hardness). Waters low in calcium and magnesium desired in electroplating, tanning, dyeing, and in textile manufacturing.
Sodium (Na) and Potassium (K)	Dissolved from practically all rocks and soils. Found also in oil-field brines, sea water, industrial brines, and sewage.	Large amounts, in combination with chloride, give a salty taste. Moderate quantities have little effect on the usefulness of water for most purposes. Sodium salts may cause foaming in steam boilers and a high sodium content may limit the use of water for irrigation.
Bicarbonate (HCO_3) and Carbonate (CO_3)	Action of carbon dioxide in water on carbonate rocks such as limestone and dolomite.	Bicarbonate and carbonate produce alkalinity. Bicarbonates of calcium and magnesium decompose in steam boilers and hot water facilities to form scale and release corrosive carbon-dioxide gas. In combination with calcium and magnesium, cause carbonate hardness.
Sulfate (SO_4)	Dissolved from rocks and soils containing gypsum, iron sulfides, and other sulfur compounds. Commonly present in some industrial wastes.	Sulfate in water containing calcium forms hard scale in steam boilers. In large amounts, sulfate in combination with other ions gives bitter taste to water. Texas Department of Health (1988) drinking water standards recommend that the sulfate content should not exceed 300 mg/l.
Chloride (Cl)	Dissolved from rocks and soils. Present in sewage and found in large amounts in oil-field brines, sea water, and industrial brines.	In large amounts in combination with sodium, gives salty taste to drinking water. In large quantities, increases the corrosiveness of water. Texas Department of Health (1988) drinking water standards recommend that the chloride content should not exceed 300 mg/l.

Table 4. (cont.)--Source, Significance, and Concentrations of Dissolved Mineral Constituents and Properties of Water

Constituent or Property	Source or Cause	Significance
Fluoride (F)	Dissolved in small to minute quantities from most rocks and soils. Added to many waters by fluoridation of municipal supplies.	Fluoride in drinking water reduces the incidence of tooth decay when the water is consumed during the period of enamel calcification. However, it may cause mottling of the teeth, depending on the concentration of fluoride, the age of the child, amount of drinking water consumed, and susceptibility of the individual (Maier, 1950, p. 1120-1132).
Nitrate (NO3) or Nitrate (as N)	Decaying organic matter, sewage, fertilizers, and nitrates in soil.	Concentration much greater than the local average may suggest pollution. Texas Department of Health (1988) drinking water standards suggest a limit of 45 mg/l (as NO3) or 10 mg/l (as N). Waters of high nitrate content have been reported to be the cause of methemoglobinemia (an often fatal disease in infants) and therefore should not be used in infant feeding (Maxcy, 1950, p 271). Nitrate shown to be helpful in reducing inter-crystalline cracking of boiler steel. It encourages growth of algae and other organisms which produce undesirable tastes and odors.
Boron (B)	A minor constituent of rocks and of natural waters.	An excessive boron content will make water unsuitable for irrigation. Wilcox (1955, p. 11) indicated that a boron concentration of as much as 1.0 mg/l is permissible for irrigating sensitive crops; as much as 2.0 mg/l for semitolerant crops; and as much as 3.0 mg/l for tolerant crops. Crops sensitive to boron include most deciduous fruit and nut trees and navy beans; semitolerant crops include most small grains, potatoes and some other vegetables, and cotton; and tolerant crops include alfalfa, most root vegetables, and the date palm.
Dissolved solids	Chiefly mineral constituents dissolved from rocks and soils.	Texas Department of Health (1988) drinking water standards recommend that waters containing more than 1,000 mg/l dissolved solids not be used if other less mineralized supplies are available. For many purposes the dissolved-solids content is a major limitation on the use of water. A general classification of water based on dissolved-solids content, in ppm, is as follows (Winslow and Kister, 1956, p. 5): Waters containing less than 1,000 ppm of dissolved solids are considered fresh; 1,000 to 3,000 ppm slightly saline; 3,000 to 10,000 ppm moderately saline; 10,000 to 35,000 ppm very saline; and more than 35,00 ppm brine.

Table 4. (cont.)--Source, Significance, and Concentrations of Dissolved Mineral Constituents and Properties of Water

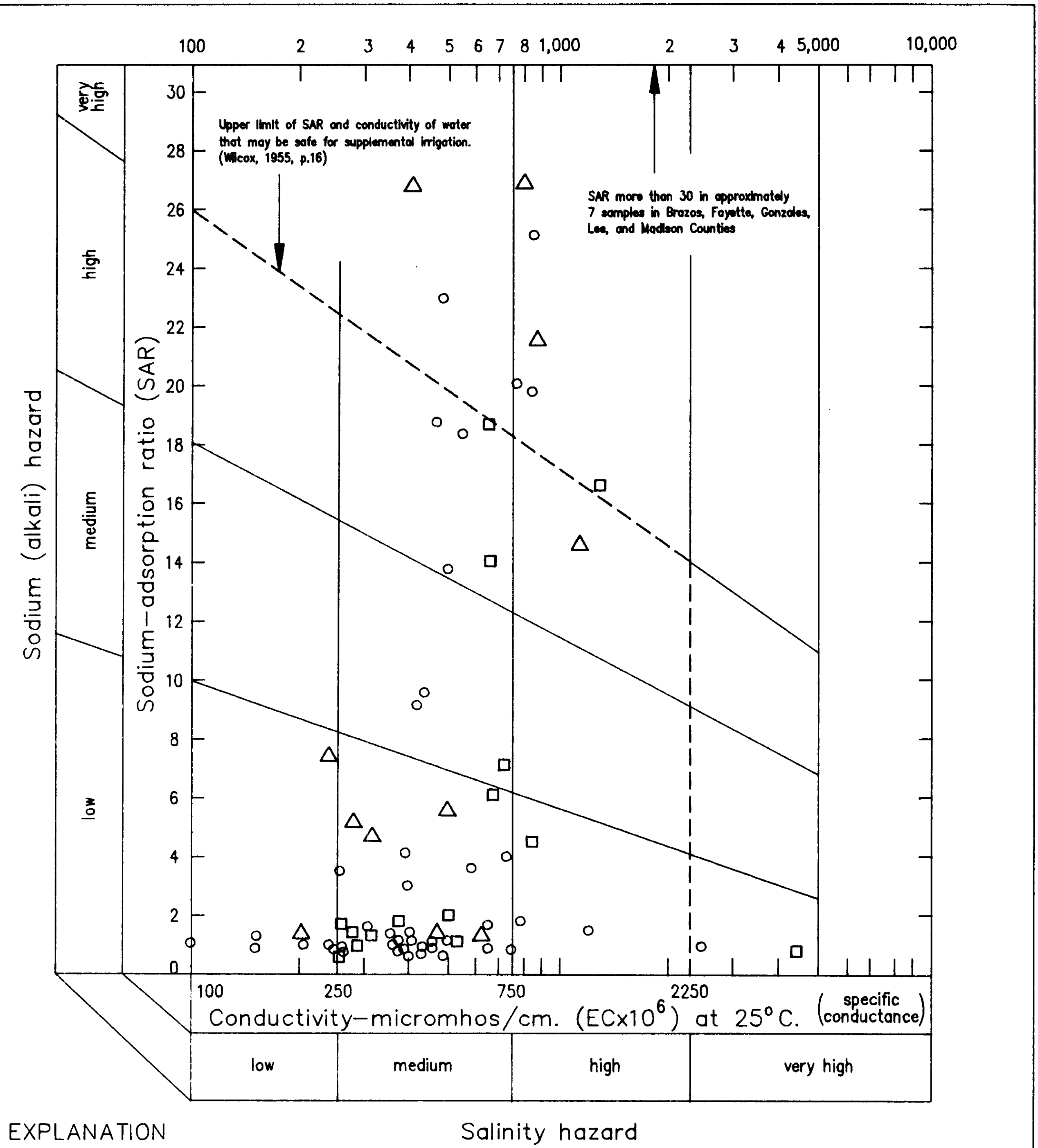
Constituent or Property	Source or Cause	Significance
Hardness as CaCO3	In most waters nearly all the hardness is due to calcium and magnesium. All of the metallic cations other than the alkali metals also cause hardness.	Consumes soap before a lather will form. Deposits soap curd on bathtubs. Hard water forms scale in boilers, water heaters, and pipes. Harness equivalent to the bicarbonate and carbonate is called carbonate hardness. Any hardness in excess of this is called non-carbonate hardness. Waters of hardness up to 60 mg/l are considered soft 61 to 120 mg/l, moderately hard; 121 to 180 mg/l, hard; more than 180 mg/l, very hard.
Percent Sodium (% Na)	Sodium in water.	A ratio (using milliequivalents per liter) of the sodium ions to the total sodium, calcium, and magnesium ions. A sodium percentage exceeding 60 percent is a warning of a sodium hazard. Continued irrigation with this type of water will impair the tilth and permeability of the soil.
Sodium-adsorption ratio (SAR)	Sodium in water.	A ratio for soil extracts and irrigation waters used to express the relative activity of sodium ions in exchange reactions with soil (U.S. Salinity Laboratory Staff, 1954, p 72, 156). Defined by the following equation: $SAR = Na^{+} \div \sqrt{\frac{Ca^{++} + Mg^{++}}{2}}$ where Na+; Ca++,and Mg++ represent the concentrations in (me/l).
Residual sodium carbonate (RSC)	Sodium and carbonate or bicarbonate in water.	As calcium and magnesium precipitate as carbonates in the soil, the relative proportion of sodium in the water is increased (Eaton, 1950, p. 123-133). Defined by the following equation: RSC = (CO3--m HCO3-) - ($Ca^{++} + Mg^{++}$) where CO3-- , HCO3-, Ca ++, and Mg ++ represent the concentrations in milliequivalents per liter (me/l) of the respective ions.
Specific conductance (micromhos at 25°C)	Mineral content of the water.	Indicates degree of mineralization. Specific conductance is a measure of the capacity of the water to conduct an electric current. Varies with concentration and degree of ionization of the constituents.
Hydrogen ion concentration (pH)	Acids, acid-generating salts, and free carbon dioxide lower the pH. Carbonates, bicarbonates, hydroxides, phosphates, silicates, and borates raise the pH.	A pH of 7.0 indicates neutrality of a solution. Values higher than 7.0 denote increasing alkalinity; values lower than 7.0 indicate increasing acidity. pH is a measure of the activity of the hydrogen ions. Corrosiveness of water generally increases with decreasing pH. However, excessively alkaline waters may also attack metals. The Texas Department of Health (1988) recommends a pH greater than 7.

Table 4. (cont.)--Source, Significance, and Concentrations of Dissolved Mineral Constituents and Properties of Water

Concentrations of constituents by Aquifer

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

		Carrizo Formation		Calvert Bluff Formation		Simsboro Formation		Hooper Formation		Wilcox Group Undifferentiated	
Silica (SiO2)	Mean	21		27		28		28		25	
	Range	1-114		1-117		5-58		2-71		5-100	
	Count	(260)		(184)		(191)		(144)		(409)	
Iron (Fe)	Mean	2.65		4.89		1.94		1.92		2.19	
	Range	0.0-73.0		0.0-73.0		0.0-49.5		0.0-20.0		0.0-46.0	
	Count	(486)		(75)		(204)		(80)		(198)	
		Ca	Mg	Ca	Mg	Ca	Mg	Ca	Mg	Ca	Mg
Calcium (Ca) and Magnesium (Mg)	Mean	27	6	51	14	35	7	57	14	61	18
	Range	0-493	0-136	1-436	0-144	0-233	0-70	2-327	0-105	0-820	0-369
	Count	(307)	(305)	(205)	(206)	(310)	(308)	(167)	(166)	(534)	(534)
		Na	K	Na	K	Na	K	Na	K	Na	K
Sodium (Na) and Potassium (K)	Mean	133	9	105	4	100	4	103	4	160	4
	Range	2-2362	0.3-475	10-1670	0.1-13	5-686	1-19	14-350	0.9-40	2-1510	0-23
	Count	(303)	(134)	(208)	(59)	(311)	(69)	(167)	(74)	(535)	(122)
		HCO3	CO3	HCO3	CO3	HCO3	CO3	HCO3	CO3	HCO3	CO3
Bicarbonate (HCO3) and Carbonate (CO3)	Mean	276	2	262	1	241	4	254	<1	300	1
	Range	0-1610	0-56	8-1260	0-33	16-1087	0-436	0-590	0-19	0-2080	0-53
	Count	(325)	(324)	(220)	(221)	(317)	(322)	(146)	(169)	(662)	(637)
Sulfate (SO4)	Mean	55		80		49		60		103	
	Range	0-1600		0-1640		0-2000		0-533		0-1800	
	Count	(324)		(221)		(322)		(179)		(682)	
Chloride (Cl)	Mean	74		104		80		118		167	
	Range	3-4000		5-3480		6-810		5-1160		3-1940	
	Count	(331)		(223)		(326)		(177)		(682)	
Fluoride (F)	Mean	<1		<1		<1		<1		<1	
	Range	0-8		0-3		0-2		0-1		0-6	
	Count	(277)		(184)		(265)		(154)		(406)	
Nitrate (NO3) or Nitrate (as N)	Mean	1.6		2.7		1.3		6.3		7.4	
	Range	0.0-83.0		0.0-144.0		0.0-21.0		0.0-128.0		0.0-540.0	
	Count	(309)		(190)		(276)		(128)		(458)	
Boron (B)	Mean	0.22		.28		.16		0.14		0.34	
	Range	0.0-1.9		0.01-2.3		0.0-.5		0.0-0.6		0.0-1.6	
	Count	(47)		(37)		(19)		(13)		(23)	
Dissolved solids	Mean	464		470		403		506		648	
	Range	41-6700		136-2641		78-1692		0-2214		27-5211	
	Count	(315)		(208)		(311)		(168)		(666)	
Hardness as CaCO3	Mean	91		216		132		215		231	
	Range	1-1790		5-2840		2-1900		0-3000		3-3483	
	Count	(320)		(222)		(318)		(179)		(553)	
Percent Sodium (% Na)	Mean	70		54		55		54		59	
	Range	9-99		10-99		10-99		4-98		5-99	
	Count	(299)		(205)		(307)		(165)		(527)	
Sodium-adsorption ratio (SAR)	Mean	12.9		6.5		9.5		4.7		10.3	
	Range	0.2-99.7		0.6-63.4		0.4-73.4		0.5-29.2		0.1-142.4	
	Count	(298)		(205)		(307)		(165)		(527)	
Residual sodium carbonate (RSC)	Mean	3.4		2.2		2.6		1.3		2.5	
	Range	0.0-26.0		0.0-20.2		0.0-16.9		0.0-6.4		0.0-32.2	
	Count	(303)		(202)		(304)		(135)		(507)	
Specific conductance (micromhos at 25°C)	Mean	731		792		660		854		1062	
	Range	57-14,250		101-11,200		90-2900		194-5570		92-7784	
	Count	(303)		(203)		(242)		(156)		(398)	
Hydrogen ion concentration (pH)	Mean	7.4		7.6		7.4		7.6		7.7	
	Range	3.3-9.7		5.1-8.7		5.3-9.4		5.5-8.8		4.8-9.5	
	Count	(309)		(209)		(292)		(167)		(453)	



EXPLANATION

○ Bastrop, Caldwell, Fayette, and Gonzales Counties

□ Brazos, Burleson, Lee, Milam, and Robertson Counties

△ Freestone, Grimes, Leon, Limestone, and Madison Counties

Figure 7

CLASSIFICATION OF CARRIZO WATERS FOR IRRIGATION, BY COUNTIES

(After U.S. Salinity Laboratory Staff, 1954, p.80)

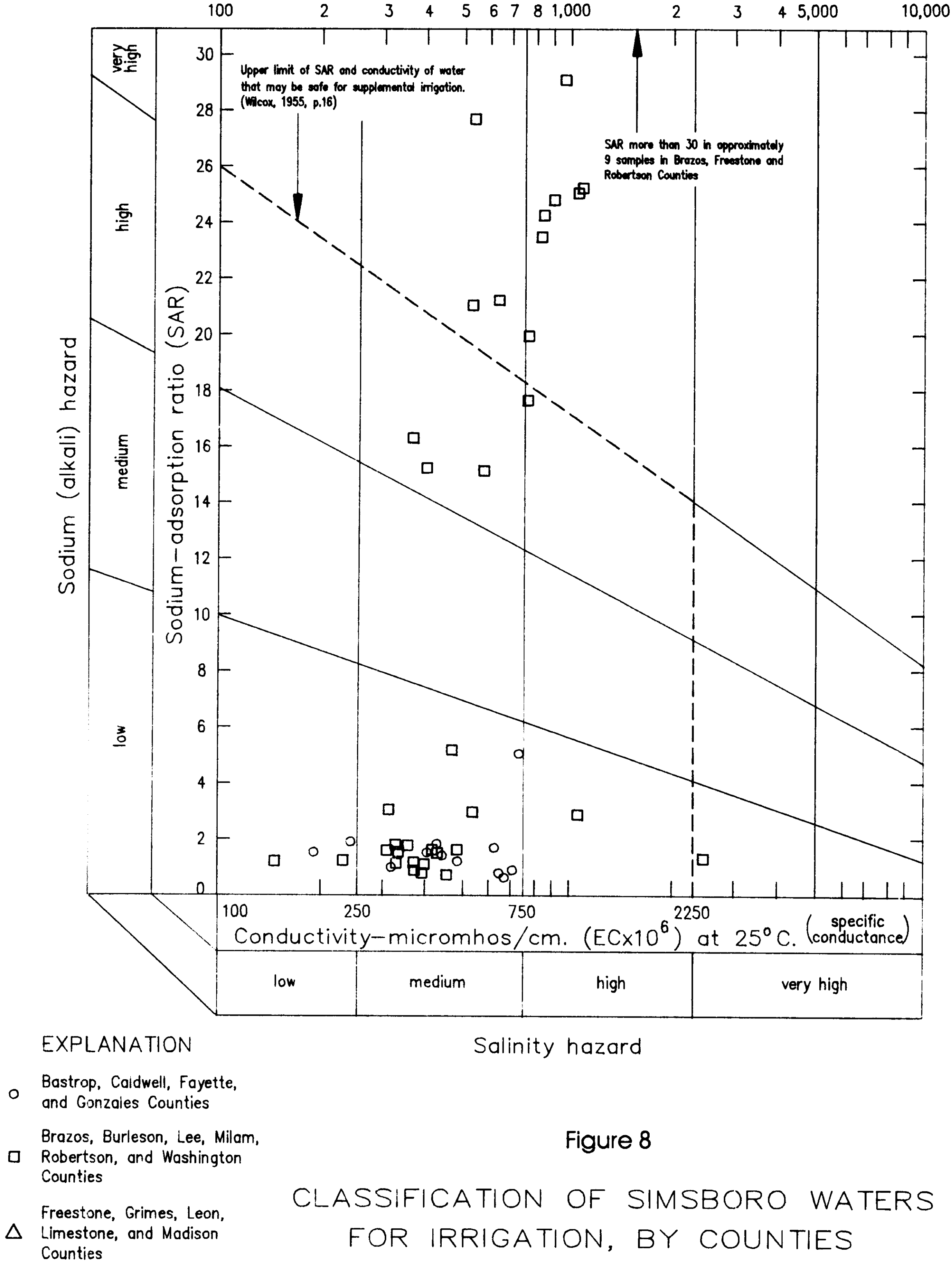


Figure 8

CLASSIFICATION OF SIMSBORO WATERS FOR IRRIGATION, BY COUNTIES

(After U.S. Salinity Laboratory Staff, 1954, p.80)

The main problem with the quality of ground water in the Carrizo-Wilcox is the presence of excessive amounts of iron. Practically all water samples contain iron to some degree and the content can vary significantly from one area to another. Fortunately, high iron concentrations can be treated by aeration, addition of chemicals, or other methods. Municipalities and industries with iron problems generally apply such methods to their water systems. Iron can present a more difficult problem in rural areas where no convenient methods for its removal are available.

Abnormally poor quality ground water is common in areas of faulting. One or more constituents may have higher concentrations in the vicinity of faults than in surrounding areas. It is believed that this may be the result of faults and fault systems forming a barrier to fresh-water circulation. Additionally, faults may provide pathways by which highly mineralized waters enter shallow fresh-water units from deeper zones. Examples of this can be seen in Caldwell and Lee Counties in areas associated with extensive faulting.

GROUND-WATER PUMPAGE AND UTILIZATION

Ground water from the Carrizo-Wilcox aquifer in the Central Texas Region is used for municipal, industrial, irrigation, and domestic and livestock purposes. Estimates of pumpage for these purposes for the period 1969-1981 are shown on Figure 9. Total pumpage in 1980 was estimated to be 40,830 acre-feet and is shown, by county, in Table 5. A total of 783 wells were inventoried for this study. This inventory does not include all of the wells that obtain water from the Carrizo-Wilcox within the study area, but it does include a record of all known municipal, industrial, and irrigation wells through the early 1980's.

Municipal

In 1980, an estimated total of 33,854 acre-feet of ground water was pumped for municipal use from the Carrizo-Wilcox. This accounts for 83 percent of the total pumpage for all purposes and is by far the major use of ground water from this aquifer. Many cities and towns including Bastrop, Bryan, College Station, Elgin, Hearne, Lockhart, Luling, and Rockdale obtain most or all of their water supplies from the Carrizo-Wilcox. The largest users of municipal water in 1980 were the cities of Bryan and College Station. Both cities secured their water primarily from the Simsboro Formation, and their total estimated pumpage was 19,367 acre-feet. This was 57 percent of the total amount for the region.

Industrial

During 1980, Bastrop, Caldwell, Freestone, Leon, Limestone, Milam, and Robertson Counties obtained ground water for industrial use from the Carrizo-Wilcox aquifer. Pumpage was estimated to be 1,751 acre-feet or about 4 percent of the total for all purposes. Over 50 percent of this amount was utilized by the Aluminum Company of America which runs an aluminum plant and lignite mine in Milam County. Other industrial uses of ground water are in oil and gas exploration, brick and rendering plants, stone quarries, and in the production of a variety of manufactured goods.

Irrigation

Total ground-water pumpage for irrigation purposes during 1980 was estimated to be 2,085 acre-feet which is 5 percent of the total pumpage. Irrigation was limited to Bastrop, Caldwell, Gonzales, Lee, and Robertson Counties. When compared to other regions of Texas, this figure is small. This is due to the fact that in the study region, rainfall is normally well distributed and provides an adequate water supply for crops throughout the year. Therefore ground water is used for irrigation only during unusually dry times.

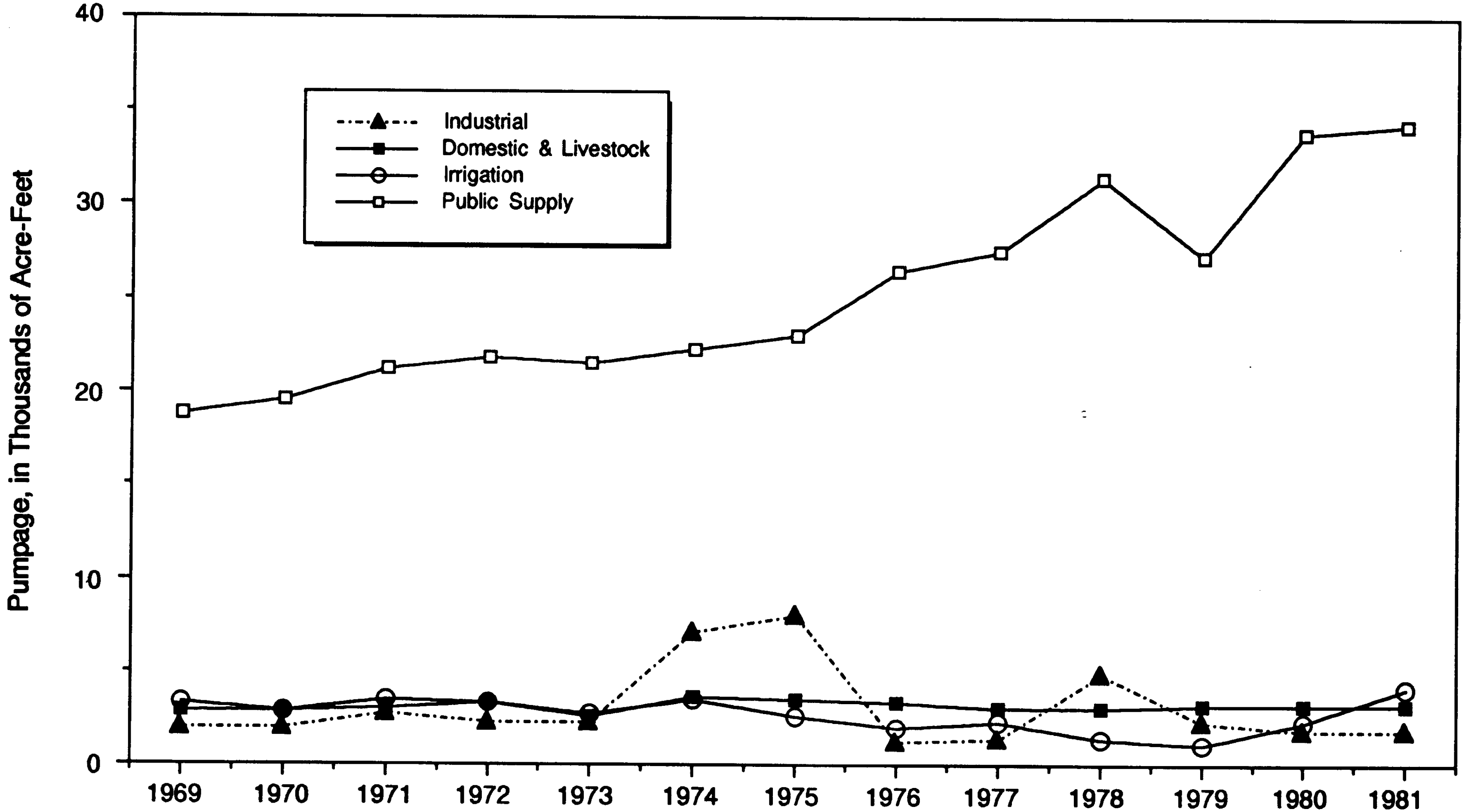


Figure 9

Estimated Ground-Water Pumpage from the Carrizo-Wilcox Aquifer Within the Study Area 1969 - 1981

Table 5.— Estimated 1980 Ground-Water Pumpage From the Carrizo-Wilcox Aquifer for Selected Counties

County	Pumpage, in acre-feet				
	Municipal	Industrial	Irrigation	Domestic and Livestock	Total
Bastrop	3,549	76	665	369	4,659
Brazos	19,367	0	0	2	19,369
Burleson	783	0	0	28	811
Caldwell	1,719	1	70	94	1,884
Falls	0	0	0	9	9
Fayette	0	0	0	0	0
Freestone	1,430	119	0	483	2,032
Gonzales	118	0	475	442	1,035
Lee	725	0	125	368	1,218
Leon	928	161	0	389	1,478
Limetone	0	398	0	52	450
Madison	0	0	0	43	43
Milam	2,341	968	0	361	3,670
Navarro	0	0	0	30	30
Robertson	2,894	28	750	461	4,133
Wiliamson	0	0	0	9	9
TOTAL	33,854	1,751	2,085	3,140	40,830

Domestic and Livestock

Estimated domestic and livestock pumpage from the Carrizo-Wilcox aquifer totaled 3,140 acre-feet in 1980 which is second only to municipal use, but still makes up only eight percent of the total pumpage. The majority of domestic and livestock wells are relatively shallow and located on the outcrop of the aquifer or in shallow artesian areas. As the Carrizo-Wilcox increases in depth, suitable water supplies are more easily obtained form other, shallower water-bearing units.

GROUND-WATER AVAILABILITY IN THE CARRIZO-WILCOX AQUIFER

As part of this regional study, one of the objectives of the investigation was to obtain reliable geohydrologic data sufficient to evaluate the long-term regional water-supply capabilities of the Carrizo-Wilcox aquifer in Central Texas. To evaluate the capabilities of the aquifer, a computerized mathematical representation in the form of a modular three-dimensional finite-difference ground-water flow model was constructed on the north one-half of the study area (McDonald and Harbaugh, 1984). This encompassed the region between the Trinity and Brazos Rivers. Following verification of the model, several water-development schemes were considered, based on different pumpage scenarios. From these runs, revised average annual ground-water availability data for the Carrizo-Wilcox aquifer were determined for the area between the Trinity and Brazos Rivers. A similar model is currently being constructed on the south one-half of the study area. Detailed discussions of the methodologies used to derive these data and a documentation of the two models will be presented in a forthcoming report. Discussion of partial results from these runs follows.

Steady-state model runs for the area between the Trinity and Brazos Rivers, under present-day conditions of pumpage and water-level gradient, indicate that the average annual effective recharge to the outcrop is about 97,600 acre-feet (2.69 percent of the mean annual rainfall over the outcrop area). About 23,200 acre-feet are available as leakage through younger beds from above, giving a total annual perpetual average availability of 120,800 acre-feet. Of this, 61,600 acre-feet are available in the Trinity River basin and 59,200 acre-feet in the Brazos River basin. Model data confirm that both the annual effective recharge to the outcrop and leakage from above, through younger beds, can be increased by greater pumpage of the aquifer.

Using a future pumpage scenario which was considered by the authors to be realistic and one which would not cause dewatering of the aquifer or deterioration in quality, the perpetual average annual availability for the area between the Trinity and Brazos Rivers was increased to about 449,600 acre-feet. Of this, about 183,500 acre-feet are projected as annual effective recharge to the outcrop (5.1 percent of the mean annual rainfall over the outcrop) and about 266,100 acre-feet as annual leakage through younger beds from above. Approximately 229,300 acre-feet per year of this total is considered available from the Trinity River basin and 220,300 acre-feet per year from the Brazos River basin. Board projections of future requirements for the area, however, do not indicate the demand will approach this amount, illustrating the great potential, on a regional scale, for future development of the Carrizo-Wilcox aquifer. Complete revised availability data and data on the amounts of total and recoverable ground water in storage within the Carrizo-Wilcox aquifer in the study area will be included in a forthcoming report.

SUMMARY

The study area of the Carrizo-Wilcox aquifer in Central Texas covers approximately 6,000 square miles and lies within the Trinity, Brazos, Colorado, and Guadalupe River basins. It includes all or part of Bastrop, Brazos, Burleson, Caldwell, Falls, Fayette, Freestone, Gonzales, Grimes, Lee, Leon, Limestone, Madison, Milam, Navarro, Robertson, and Williamson Counties.

This aquifer system is made up of the Carrizo Formation and the Wilcox Group which were deposited in Texas by large river and delta systems during Tertiary time. The Wilcox Group, in much of central Texas area, is further divided into the Hooper, Simsboro, and Calvert Bluff Formations. Hydrologic connection often exists between the formations and, in this report, the formations are considered as one regional flow system. The Carrizo and Simsboro Formations are the most dominant of these water-bearing units.

Precipitation is the main source of recharge to the Carrizo-Wilcox. A substantial amount of recharge is rejected in the outcrop. Computer simulations on the north one-half of the study area, between the Trinity and Brazos Rivers, indicate that less than 3 percent, or about 97,600 acre-feet, of the mean annual rainfall on the outcrop actually becomes recharge to the aquifer. An additional 23,200 acre-feet of ground water is obtained annually from overlying younger units through interformational leakage. This gives a total annual availability of 120,800 acre-feet for this area under present day conditions. Similar computer simulations are being performed on the area from the Brazos to the Colorado Rivers, and recharge and availability figures for this area will be presented in a forthcoming report.

Due to the complex distribution of sands and clays in the Carrizo-Wilcox, hydraulic characteristics vary significantly from one area to another. Direction and rate of flow also exhibit a similar variance. In the outcrop area, ground-water movement is controlled by topography and pumpage and ground water travels in the direction of decreasing head or pressure. Downdip in the artesian section, movement generally follows the regional dip of the formations. Some ground water seeps upward through semi-confining beds into younger units due to the difference in hydrostatic pressure between the individuals units of the aquifer. Flow rates in the Carrizo-Wilcox can be extremely small or as much as several hundred feet per year in areas of accumulations of conductive sand. Generally, flow rates range from 10 to 100 feet per year.

Regionally, water from the Carrizo-Wilcox is fresh to slightly saline and is suitable to use for all purposes with little or no treatment. With relatively few exceptions, concentrations of all chemical constituents satisfy standards set by the Texas Department of Health. Locally, however, abnormally high levels of some constituents may occur. Excessive iron concentration is the most common problem in the Carrizo-Wilcox, and some water supplies must be treated to remove it. Areas of extensive faulting also have the potential to produce poorer quality ground water due to the restriction of normal flow patterns and possible mixing with poorer quality water entering the aquifer along fault planes from other formations.

Well yields from the Carrizo-Wilcox aquifer range from less than 100 to more than 2,500 gal/min. The largest yields are obtained from wells completed in the Carrizo and Simsboro Formations.

Approximate total pumpage from the Carrizo-Wilcox aquifer in the central Texas study area during 1980 was about 40,800 acre-feet. Of this total, 83 percent was used for public supply, 8 percent for rural domestic and livestock needs, 5 percent for irrigation, and 4 percent for industrial purposes. Projected future water demands do not indicate significant increases in the amount of water necessary to meet projected requirements. Therefore, the Carrizo-Wilcox aquifer should remain a valuable and reliable source of ground water to the central Texas region. It should be remembered, however, that any well fields developed in this aquifer should have the proper spacing, utilize all available sands, and have designed well screens.

SELECTED REFERENCES

Ahmad, M.U., 1983, A quantitative model to predict a safe yield for well fields in Kufra and Sarir Basins, Libya: Ground Water, v. 21, no. 1, p. 58-66.

American Commission on Stratigraphic Nomenclature, 1961, Code of stratigraphic nomenclature: Am. Assoc. Petroleum Geologists Bull., v. 45, no. 5, p. 645 - 665.

Anders, R.B., 1957, Ground-water geology of Wilson County, Texas: Texas Board Water Engineers Bull. 5710, 66 p.

Ayers, W.B., Jr., and Lewis, A.H., 1985, The Wilcox Group and Carrizo Sand (Paleogene) in east-central Texas - depositional systems and deep-basin lignite: The University of Texas at Austin, Bureau of Economic Geology Geologic and Hydrological Folio, Wilcox Group, East Texas, 19 p.

Baker, E.T., Jr., Follett, C.R., McAdoo, G.D., and Bonnet, C.W., 1974, Ground-water resources of Grimes County, Texas: Texas Water Devel. Board Rept. 186, 109 p.

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

Barnes, V.E., 1965, Tyler sheet: The University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale: 1:250,000.

____, 1968a, Beaumont sheet: The University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale: 1:250,000.

____, 1968b, Palestine sheet: The University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale: 1:250,000.

____, 1970, Waco sheet: The University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale: 1:250,000

____, 1972, Dallas sheet: The University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale: 1:250,000

____, 1974a, Austin sheet: The University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale: 1:250,000

____, 1974b, Seguin sheet: The University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scal e: 1:250,000

Beard, D.C. and Weyl, P.K., 1973, Influence of texture on porosity and permeability of unconsolidated sand: Am. Assoc. Petroleum Geologists Bull., v.57, no. 2, p. 349-369.

Chuber, Stewart, 1979, Exploration methods of discovery and development of lower Wilcox reservoirs in Valentine and Menking fields, Lavaca County, Texas: Gulf Coast Assoc. of Geological Societies Transactions, v. 29, p. 42-51.

Cronin, J.G., and Wilson, C.A., 1967, Ground water in the floodplain alluvium of the Brazos River, Whitney Dam to vicinity of Richmond, Texas: Texas Water Devel. Board Rept. 41, 206 p.

Dallas Morning News, 1979, Texas Almanac and state industrial guide, 1980- 81: A .H. Belo Corp., 704 p.

Edwards, M.B., 1981, Upper Wilcox Rosita delta system of south Texas: growth-faulted shelf-edge deltas: Am. Assoc. Petroleum Geologists Bull., v. 65, no. 1, p. 54-73.

Fetter, C.W., Jr., 1980, Applied hydrogeology: Columbus, OH, Merrill Publishing Co., 448 p.

Fisher, W.L., 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., and Kreitler, C.W., 1981, Ground-water hydrology around salt domes in the East Texas Basin - a practical approach to the contaminant transport problem: Bull. of the Assoc. of Engineering Geologists, v. 18, no. 4, p. 387-411.

____, 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 p.

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 p.

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

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

____, 1974, Ground-water resources of Brazos and Burleson Counties, Texas: Texas Water Devel. Board Rept. 185, 194 p.

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

Hargis, R.N., 1962, Stratigraphy of the Carrizo-Wilcox of a portion of south Texas and its relationship to production: Gulf Coast Assoc. of Geological Societies Transactions, v. 12, p. 9-25.

Henry, C.D., 1976, Land resources inventory of lignite strip-mining areas, east Texas - an application of environmental geology: The University of Texas at Austin, Bureau of Economic Geology Geological Circ. 76-2, 28 p.

Henry, C.D., and Basciano, J.M., 1979, Environmental geology of the Wilcox Group lignite belt, east Texas: The University of Texas at Austin, Bureau of Economic Geology Rept. of Investigations No. 98, 28 p.

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

Hoffman, H.W., Jr., 1980, The impact of strip mining and use on water resources in Texas – a brief overview: Texas Civil Engineer, v. 50, no. 6, p. 14-19.

Hoyt, W.V., 1959, Erosional channel in the middle Wilcox near Yoakum, Lavaca County, Texas: Gulf Coast Assoc. of Geological Societies Transactions, v. 9, p. 41- 50.

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 p.

____, 1976, Calvert Bluff (Wilcox Group) sedimentation and the occurrence of lignite at Alcoa and Butler, Texas: The University of Texas at Austin, Bureau of Economic Geology Research Note 2, 10 p.

Kaiser, W.R., , 1978, Depositional systems in the Wilcox Group (Eocene) of east-central Texas 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, p. 33-53.

Kaiser, W.R., ,Ayers, W.B., Jr., and LaBrie, L.W., 1980, Lignite resources in Texas: The University of Texas at Austin , Bureau of Economic Geology Rept. of Investigations No. 104, 52 p.

Kaiser, W.R., ,et. al., 1986, Geology and ground-water hydrology of deep-basin lignite in the Wilcox Group of east Texas: The University of Texas at Austin, Bureau of Economic Geology Other Report, 182 p.

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

Keys, W.S., and McCary, L.M., 1971, Application of borehole geophysics to water- resources investigations, in U. S. Geol . Survey , Techniques in wa ter- resources investigations: Chapter El , Book 2, 124 p.

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 p. and 466 p., respectively.

Kreitler, C.W., Agagu, O.K., Basciano, J.M., Collins, E.W., Dix, O.R., Dutton, S.P., Fogg, G.E., Giles, A.B., Guevara, E.H., Harris, D.W., Hobday, D.K., McGowan, M.K., Pass, D., and Wood, D.H., 1980, Geology and geohydrology 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 p.

Kreitler, C.W., Davidson, D.E., Dix, O.R., Donaldson, G.A., Dutton, S.P., Collins, E.W. , Fogg, G.E., Giles, A. B., Harris, D. W. , Jackson, M. P. A., Lopez, C. M., McGowen, M. K., Seni, S. J., and Wood, D. H., 1981. Evaluating the potential of east Texas salt domes for isolation of nuclear wastes: The Univiersity of Texas at Austin, Bureau of Economic Geology Geological Circ. 81- 7, 207 p.

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

Law, B.E., Hatch, J.R., Kukal, G.C., and Keighin, C.W., 1983, Geologic implications of coal dewatering: Am. Assoc. Petroleum Geologists Bull., v. 67, no. 12, p. 2255-2260.

Lohman, S.W., 1972, Ground-water hydraulics: U.S. Geol. Survey Professional Paper 708, 70 p.

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 p.

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 p.

Muller, D.A., and Price, R.D., 1979, Ground-water availability in Texas – estimates and projections through 2030: Texas Dept. of Water Resources Rept . 238, 77 p.

Payne, J.N., 1975, Geohydrologic significance of lithofacies of the Carrizo and of Arkansas, Louisiana, Texas and the Meridian sand of Mississippi: U. S. Geol . Survey Professional Paper 569-D, 11 p.

Peckham, R.C., 1965, Availability and quality of ground water in Leon County, Texas: Texas Water Comm. Bull. 6513, 44 p.

Pennequin, D.F.E., 1983, Ground-water flow model determinations of areal hydrogeology and geology: Ground Water, v. 21, no. 5, p. 552 - 557.

Plummer, F.B., 1932, Cenozoic systems in Texas, in The Geology of Texas, v. 1, stratigraphy: Univ. Texas Bull. 3232 [1933], p. 519 - 818.

Pollack, C.R., 1983, Long term impacts on ground water in Texas delta plain lignite mines: Bull. of the Asso. of Engineering Geologists, v. 20, no. 1, p. 1 - 4.

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

Sandeen, W.M., 1972, Ground-water resources of Washington County, Texas: Texas Water Devel. Board Rept. 162, 105 p.

Scalapino, R.A., 1963, Ground-water conditions in the Carrizo sand in Texas: Ground-Water Jour. of the Nat'l. Water Well Assoc., v. 1, no. 4, p. 26 - 32.

Shafer, G.H., 1965, Ground-water resources of Gonzales County, Texas: Texas Water Devel. Board Rept. 4, 89 p.

____,1966, Ground-water resources of Guadalupe County, Texas: Texas Water Devel. Board Rept. 19, 95 p.

Texas Department of Health, 1988, Drinking water standards governing drinking water quality and reporting requirements for public water supply systems: Texas Dept. Health Report.

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

____1972, Ground-water resources of Navarro County, Texas: Texas Water Devel. Board Rept. 160, 63 p.

Todd, T.W., and Folk, R.L., 1957, Basal Claiborne of Texas, record of Appalachian tectonism during Eocene: Am. Assoc. Petroleum Geologists Bull., v. 41, no. 11, p. 2545 - 2566.

Torak, L.J., and Whiteman, C.D., Jr., 1982, Applications of digital modeling for evaluating the ground-water resources of the "2,000-foot" sand of the Baton Rouge area, Louisiana: Louisiana Dept. of Transportation and Development Technical Rept. 27, 87 p.

Toth, J., 1978, Gravity-induced cross-formational flow of formation fluids, Red Earth Region, Alberta, Canada: analysis, patterns, and evolution: Water Resources Research, v. 14, no. 5, p. 805-843.

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

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

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