Report 337

Evaluation of Water Resources in Parts of the Rolling Prairies Region of North-Central Texas

March 1992

Texas Water Development Board

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ABSTRACT

The evaluation of ground-water resources in parts of the Rolling Prairies Region of north-central Texas is in response to the 1985 passage of House Bill 2 by the Sixty-ninth Texas Legislature. This bill called for the identification and study of areas in the State that are experiencing or are expected to experience critical underground water problems within the next 20 years. The study area which lies within the Brazos, Colorado, Red, and Trinity River Basins, includes all or parts of Archer, Armstrong, Baylor, Briscoe, Callahan, Childress, Clay, Collingsworth, Cottle, Crosby, Dickens, Donley, Eastland, Erath, Fisher, Floyd, Foard, Garza, Hall, Hardeman, Haskell, Jack, Jones, Kent, King, Knox, Montague, Motley, Nolan, Palo Pinto, Parker, Randall, Scurry, Shackelford, Stephens, Stonewall, Swisher, Taylor, Throckmorton, Wheeler, Wichita, Wilbarger, Wise, and Young Counties.

Based on the U.S. Bureau of Census most recent statistics, the region generally has a declining population, continuing trends established during the 1970s. The decline in population can be attributed to many reasons, but the paramount ones among these appear to be changes in technology and activity in the petroleum and agri-business sectors. In the larger metropolitan areas, however, manufacturing activity seems to have provided an influence for stabilization or even an increase in population growth.

A recognized ground water problem in the area is the natural pollution of surface water from salt springs and seeps issuing from the Permian. Water from the Blaine is usually very hard and contains dissolved solids ranging from 1,000 to over 10,000 mg/l, and high in sodium and chloride. This water is primarily used for irrigation. However, irrigation may be limited in some areas due to soil type, surface slope, and moderate to very high sodium and salinity hazards of the water. High sulfate content limits its use for municipal supply.

Dissolved solids concentration in the Triassic Dockum aquifer varies from less than 500 to 10,000 mg/l dissolved solids. Water from the aquifer is primarily used for municipal, irrigation, and oil field water-flooding purposes. Water hardness in parts of the study area is very high and fluoride content marginal making some of the water unacceptable for municipal, irrigation, and industrial use.

Water quality of the Quaternary Seymour aquifer is variable throughout the study area. In some areas the salinity has increased with pumping to the point that the water has become unsuitable for domestic and municipal uses. The sulfate content of the aquifer, which often exceeds the secondary drinking standard of 300 mg/l, varies greatly throughout the region. Abnormally high nitrate concentrations occur in the Seymour over a wide geographic area, especially in Haskell and Knox Counties.

Additionally, localized aquifers are commonly the only source of ground water. These aquifers provide small to moderate quantities of fresh to moderately saline water for public supply, irrigation, domestic, and livestock uses.

Water levels in the Blaine and Dockum aquifers have generally risen, while the Seymour aquifer undergoes seasonal fluctuations in water levels which correspond to changes in rainfall and irrigation pumpage. Long-term water-level declines in the Seymour aquifer were observed in wells belonging to the Cities of Vernon and Childress.

In 1988, the total pumpage of ground water was about 136,632 acre-feet, of which 81 percent was used for agricultural irrigation. The total annual water requirement is projected to increase by approximately 30 percent from 1990 to 2010. Ground-water and surface-water supplies are adequate to meet current and projected needs through the year 2010; however, water-quality problems will continue to exist in some areas.

INTRODUCTION

Purpose

In 1985, the Texas Legislature recognized that certain areas of the State were experiencing critical ground-water problems or will experience them in the future. This study of ground-water conditions in north-central Texas is in response to the passage of House Bill 2 by the Sixty-ninth Texas Legislature that called for the identification of critical ground-water areas in the State. The purpose of this report is to describe the geohydrologic conditions that exist in parts of the Rolling Prairies region of north-central Texas and to identify problems related to the occurrence and development of water resources in the region with special emphasis on current and potential water quality problems, both natural and man-induced.

Location and Extent

The area covered by this report is located in the Rolling Prairies Region of the North Central Plains of Texas as shown on Figure 1. The area covers approximately 29,200 square miles and represents about 11 percent of the total area of the State of Texas. The study area includes all or parts of forty-four counties: Archer, Armstrong, Baylor, Briscoe, Callahan, Childress, Clay, Collingsworth, Cottle, Crosby, Dickens, Donley, Eastland, Erath, Fisher, Floyd, Foard, Garza, Hall, Hardeman, Haskell, Jack, Jones, Kent, King, Knox, Montague, Motley, Nolan, Palo Pinto, Parker, Randall, Scurry, Shackelford, Stephens, Stonewall, Swisher, Taylor, Throckmorton, Wheeler, Wichita, Wilbarger, Wise, and Young. The study area lies within the Brazos, Colorado, Red, and Trinity River Basins.

Topography and Drainage

The study area is located within the West Texas Rolling Prairies Section of the North Central Plains physiographic province. The surface of the area constitutes, for the most part, a gently eastward sloping plain dissected by well established systems of drainage.

Drainage of the region is toward the east and southeast in the direction of the general slope of the land surface. The northern part of the area is drained by the Red River and its tributaries while the southern portion is drained by the Brazos River through its two main tributaries, the Salt and Clear Forks. The southeastern part of the area is drained by the West Fork of the Trinity River.

The land surface elevation of the area ranges from about 700 feet along the main river valleys in the east to nearly 2,600 feet at the base of the High Plains escarpment in the northwest. The land surface is level to rolling, broken by the drainage systems consisting of wide valleys bounded by abrupt embankments. The surface is typically quite hilly along the breaks of the High Plains escarpment in the southwesternmost part of the area.

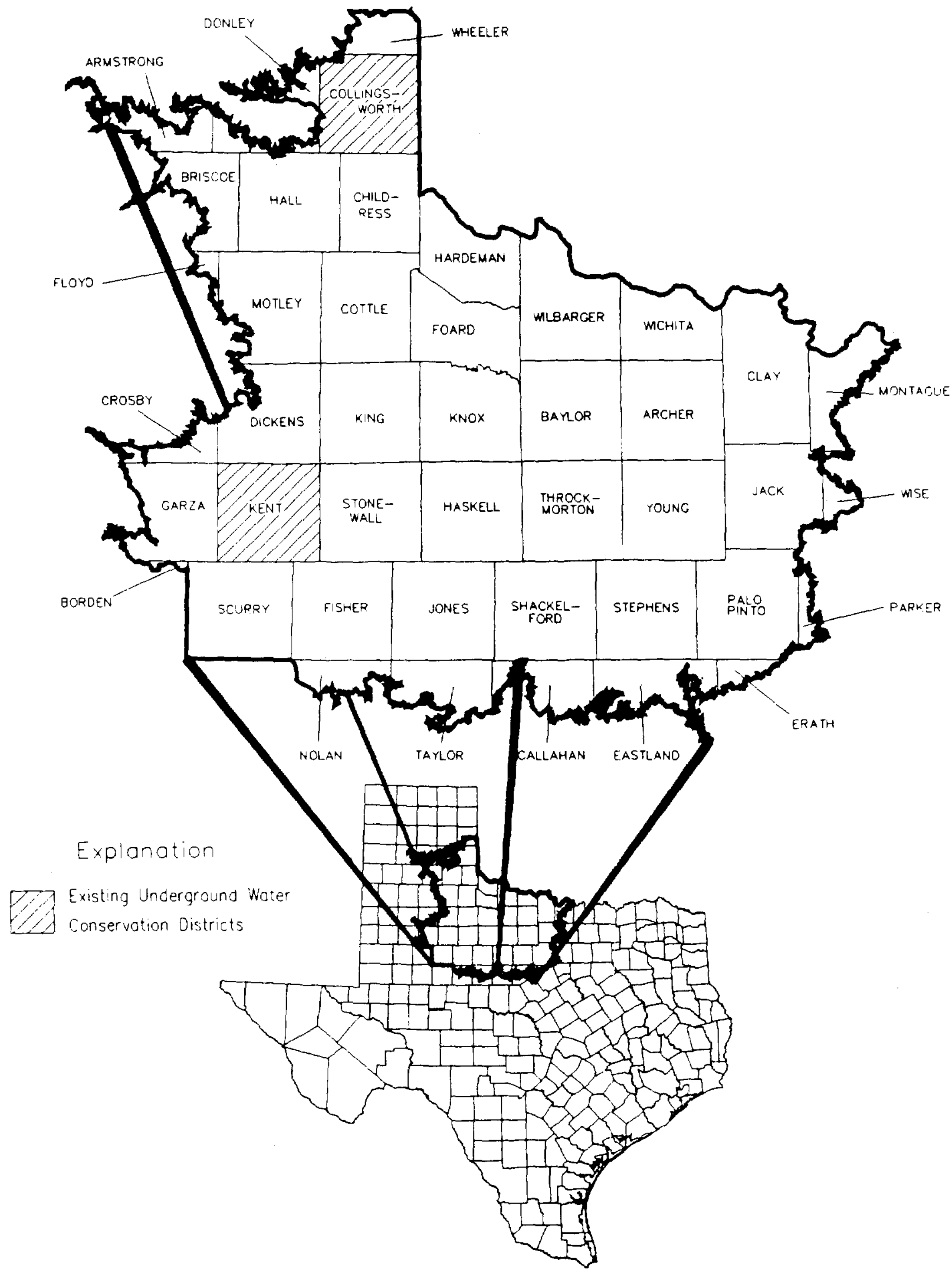


Figure 1

LOCATION OF STUDY AREA

Climate

The study area is characterized by hot summers and dry winters. The average annual precipitation ranges from about 32 inches in the eastern part to about 20 inches in the west. The average gross lake surface evaporation rate of 70 inches is more than twice the amount of the average annual precipitation. The average monthly low temperature for January ranges from about 22°F in the northwestern part of the area to about 32°F in the east. Average monthly high temperatures for July range from 95°F in the west to 99°F in the east.

Economy

The economy of the area is based largely on farming, ranching, and petroleum production, including an extensive infrastructure supporting and servicing these basic activities. Businesses include agribusiness, oilfield service, cotton, grain and food processing, and different manufactured products. Cities and towns located throughout the area serve as farm and ranch trading and supply centers.

Agriculture production is extensive and various. Principal crops include: cotton, wheat, and other small grains; grain sorghum; alfalfa; hay; peanuts; and some vegetables. Approximately 175,000 acres are under irrigation. Livestock production includes beef and dairy cattle, sheep, swine, and horses. Some of the State's largest ranches are located in the area.

Mineral production in the area includes oil and gas, stone, gypsum, sand and gravel, and clays. Scurry County is among the largest oil producers in the State. Of the forty-four counties in the study area, only Childress, Cottle, Dickens, and Hall produce small or insignificant quantities of oil and gas. Oil production in the area accounts for over 12 percent of the State's total production.

Manufacturing and processing, centered in cities and towns throughout the area, produce a variety of products. These include oilfield equipment, clothing, building products, plastic products, electronic components and equipment, aircraft components, mobile homes, and other recreational vehicles. Wood products and flat bed and livestock trailers are also manufactured in the area.

Abilene, the largest city in the area with a population in excess of 106,000 people, is located partly in Taylor and partly in Jones Counties towards the southern limit of the study area. Although petroleum production and oil field services are the cornerstones of the economy, Abilene is diversifying. It is a major health care center for the region. Dyess Air Force Base is also a major economic factor in the region. Institutions of higher learning in Abilene include Abilene Christian University, Hardin-Simmons University, and McMurray College.

Wichita Falls, the second largest city in the area, is situated in Wichita County along the Red River in the northern part of the study area. The city has become an important manufacturing, wholesale, retail, and distribution center for a large section of northern Texas and southern Oklahoma. Wichita County was one of the State's earliest petroleum-producing areas, and today it is a leading operations center for north Texas oil production. Sheppard Air Force Base also makes a major contribution to the economy.

Large federal expenditures, especially in the defense industries, and extensive recreational facilities contribute substantially to the area's economy. Numerous lakes provide fishing, boating, and other water sports.

Previous Investigations

Ground-water resources in the study area have been discussed in varying degrees of detail in several previously published reports. Reconnaissance level studies of the Red, Sulphur, and Cypress River basins (Baker and others, 1963), Trinity River basin (Peckham and others, 1963), and the Brazos River basin, (Cronin and others, 1963) provided general information on the geology and ground-water resources in the Rolling Prairies Region.

Since 1960, detailed reports on ground-water resources have been published on 24 of the 44 counties located within the study area. These county reports include Archer (Morris, 1967), Baylor (Preston, 1978), Briscoe (Popkin, 1973b), Callahan (Price and others, 1983), Collingsworth (Smith, 1970), Dickens (Cronin, 1972), Floyd (Smith, 1973), Hall (Popkin, 1973b), Hardeman (Maderak, 1972), Haskell (Hardin, 1978), Jack (Nordstrom, 1988), Jones (Price, 1978), Kent (Cronin, 1972), Knox (Hardin, 1978), Mitchell (Shamburger, 1967), Montague (Bayha, 1967), Motley (Smith, 1973), Nolan (Shamburger, 1967), Shackleford (Preston, 1969), Stephens (Bayha, 1964), Taylor (Taylor, 1978), Throckmorton (Preston, 1970), Wilbarger (Price, 1979), and Young (Morris, 1964).

In addition to the aforementioned publications, several reports describing geology and ground-water conditions in areas smaller than counties have been prepared. Some of these reports have been published, while others are available in the files of the Texas Water Development Board and the U.S. Geological Survey. The most important are listed in the selected reference at the end of this report.

Acknowledgments

The Texas Water Development Board wishes to express its appreciation to the many water well owners for permitting access to their properties. Special thanks are due to those well owners who, often at some inconvenience, agreed to turn on their pumps for extended periods of time to permit a water sample to be collected. Their cooperation and assistance is gratefully acknowledged.

Also special thanks are given to Fernando DeLeon with the Oil and Gas Division of the Railroad Commission of Texas for supplying references on brine contamination and for the use and modification of a computer program to help categorize and analyze samples for potential contamination. In addition, thanks are due to those public supply and industrial well owners in the region who annually participated in the Board's water-use inventory, thus providing valuable information necessary to evaluate the effects of ground-water pumpage on water level and water quality in the different aquifers.

GEOHYDROLOGY

Geologic Framework

The Rolling Prairies Region of Texas includes several prominent geologic structures as shown in Figure 2. The most important structural features affecting the ground water in the study area are the regional west-northwest dip, the development of the Fort Worth Basin, the Bend Arch, the Red River Uplift and the Eastern Midland Shelf.

Stratigraphic units that supply fresh to slightly saline water to wells in the study area range in age from Pennsylvanian to Recent. Permian, Triassic, and Quaternary formations contain the largest and most prolific aquifers. These are the Blaine Formation of the Permian Pease River Group, the Triassic Dockum Formation, and the Quaternary Seymour Formation. Other formations in stratigraphically ascending order that contain small localized quantities of fresh to moderately saline water include the following groups: Strawn, Canyon, Cisco, Wichita-Albany, Clear Fork, and the Recent alluviums along the rivers and their major tributaries. The outcrop areas of the groups and geologic units are shown in Figure 3. The stratigraphic relationship, approximate thickness, brief description, and water-bearing characteristics of the geologic units are summarized in Table 1. A hydrogeologic section portraying the structure and relationship of each stratigraphic unit is shown in Figure 4.

Several county and regional reports listed in the selected references at the end of this report present the geology of the study area in varying detail. These reports summarize the geologic history, structure, and effects of the stratigraphic frame-work on the occurrence of ground water. It is beyond the scope of this report to present a detailed description of the geology of the study area, which would repeat much of the material previously published. It is intended, however, that the condensed geologic information provided in Table 1, along with Figures 2 through 4, will be sufficient to utilize the ground-water information presented in this report.

Source and Occurrence

The formations of the Strawn Group of Middle Pennsylvanian age crop out in a north eastward-trending belt in parts of Parker, Palo Pinto, Eastland, and Erath Counties. Potable water in the Strawn is found chiefly in sandstones and conglomerates which receive recharge chiefly by precipitation on the outcrop areas. At most places along the outcrop and short distances downdip, water wells are capable of yielding small supplies of slightly to moderately saline water.

The formations of the Canyon Group of Late Pennsylvanian age crop out in a northeastward-trending belt which ranges about 6 to 20 miles wide and occupies parts of Eastland, Stephens, Palo Pinto, Young and Jack Counties. The Canyon Group consists of limestone and shale with minor amounts of sandstone and conglomerate. Much of the water pumped from the small wells drilled along the outcrop for domestic use is of poor quality; with increasing distance downdip, the water becomes even more saline.

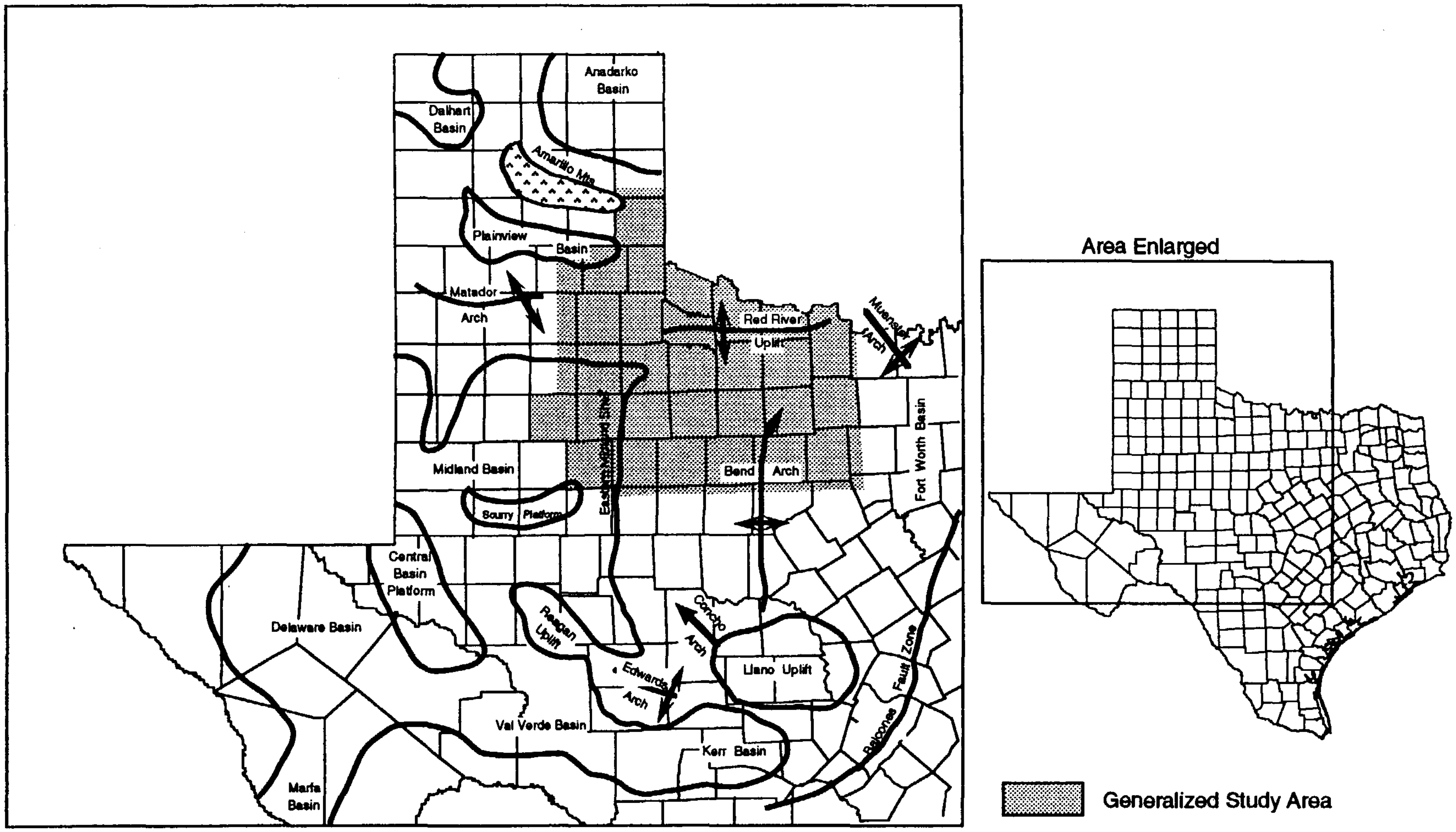


FIGURE 2
REGIONAL GEOLOGIC STRUCTURE AND LOCATION OF STUDY AREA

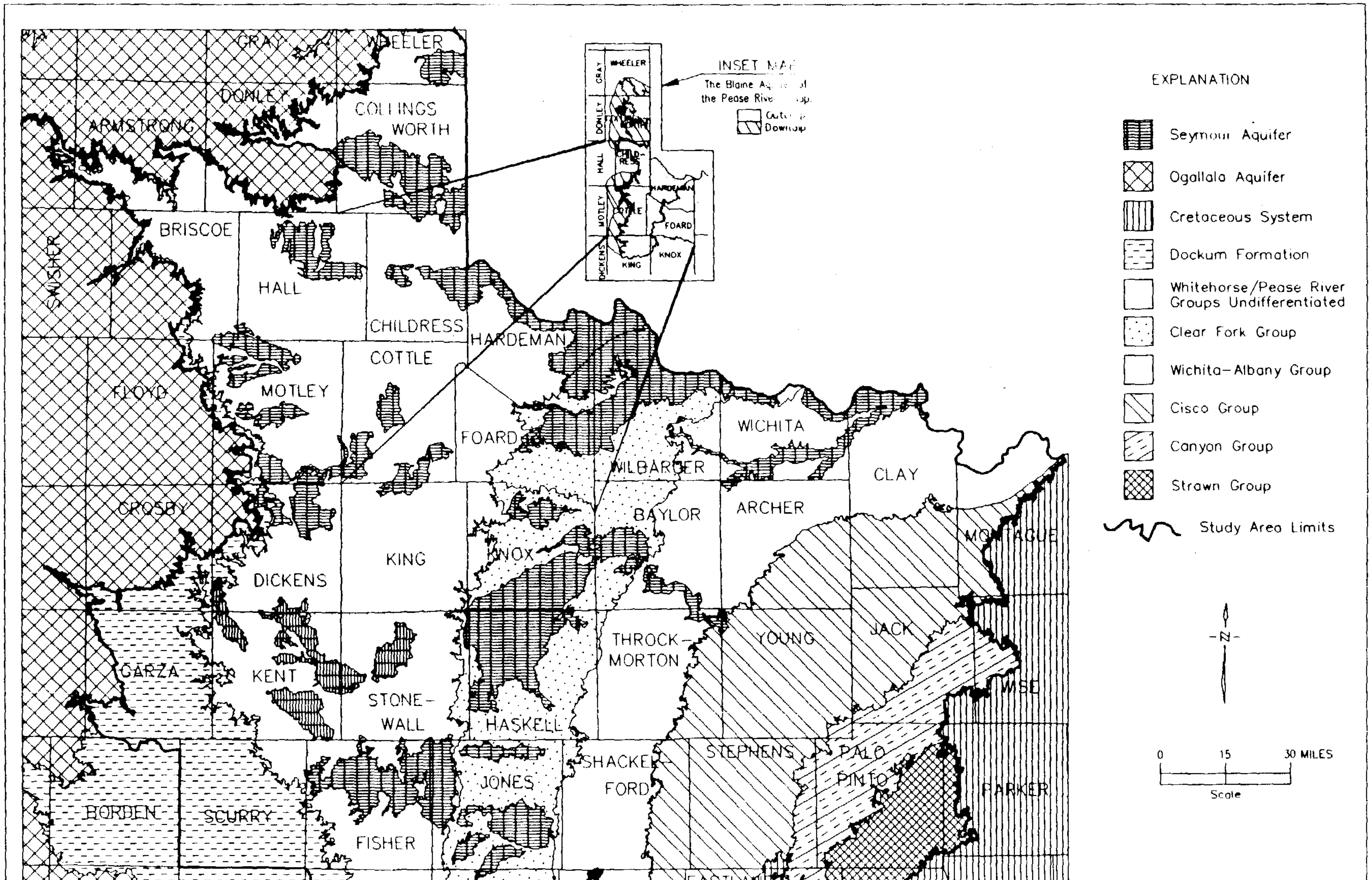


Figure 3

GEOLOGIC MAP

Source: TWDB,1990a

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

SYSTEM	GROUP / GEOLOGIC UNIT	APPROXIMATE MAXIMUM THICKNESS	CHARACTER OF ROCK	WATER-BEARING PROPERTIES*
Quaternary	Alluvium	60	Surficial flood plain and terrace alluvium along the streams consisting of gravel, sand, silt, and clay	Yields small quantities of fresh to moderately saline water to wells mainly along rivers and their major tributaries
Quaternary	Seymour Formation	125	Unconsolidated sediments of fine– to coarse–grained gravel, fine– to coarse–grained sand, silt and clay	Yields small to large quantities of fresh to moderately saline water to wells and springs
Tertiary	Ogallala Formation	—	Tan, yellow, and reddish–brown, silty to coarse–grained sand, mixed or alternating with yellow to red silty clay and variable sized gravel	Western boundary of study area
Cretaceous	Fredericksburg–Washita Groups Undifferentiated	—	Fossiliferous limestone, marl, and clay; some sand near the top	Yields small quantities of water to shallow wells
Cretaceous	Trinity Group	—	Fine to coarse sand, interbedded calcareous shale, conglomerate, limestone, clay and anhydrite	Eastern boundary of study area
Triassic	Dockum Formation	400	Clay, shale, and sandy shale, cross–bedded sandstone, conglomerate, gypsum, and anhydrite	Yields small to moderate quantities of water for domestic and livestock purposes
Permian	Whitehorse / Pease River Groups Undifferentiated (Quatermaster, Blaine, San Angelo)	1,900	Sand, sandstone, shale, gypsum, anhydrite, dolomite, and salt	Yields small to large quantities of fresh to moderately saline water for domestic, livestock, and irrigation wells
Permian	Clear Fork Group	1,800	Chiefly shale and thin beds of limestone, marl, dolomite, anhydrite, gypsum, and sandstone	Yields small quantities of slightly to moderately saline water
Permian	Wichita–Albany Group	1,400	Chiefly gray and red shale; minor amounts of limestone, sandstone, siltstone, conglomerate, and coal	Yields fresh to slightly saline water in small quantities to wells in the outcrop area
? Pennsylvanian	Cisco Group	1,200	Shale, sandstone, conglomerate, limestone, and a few beds of coal	Yields small to moderate quantities of fresh to moderately saline water for public supply, industrial, irrigation, domestic, and stock wells
Pennsylvanian	Canyon Group	1,600	Chiefly limestone and shale; minor amounts of sandstone and conglomerate	Yields small quantities of fresh to slightly saline water to wells in and near the outcrop
Pennsylvanian	Strawn Group	2,500	Alternating beds of shale, conglomerate, and sandstone; minor amounts of limestone and coal	Yields small quantities of slightly to moderately saline water from sandstone and conglomerate in and near the outcrop

* 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 milligrams per liter (mgl/) total dissolved solids: Fresh, less than 1,000 mg/l; slightly saline, 1,000–3,000 mg/l; moderately saline, 3,000–10,000 mg/l; very saline to brine, more than 10,000 mg/l.

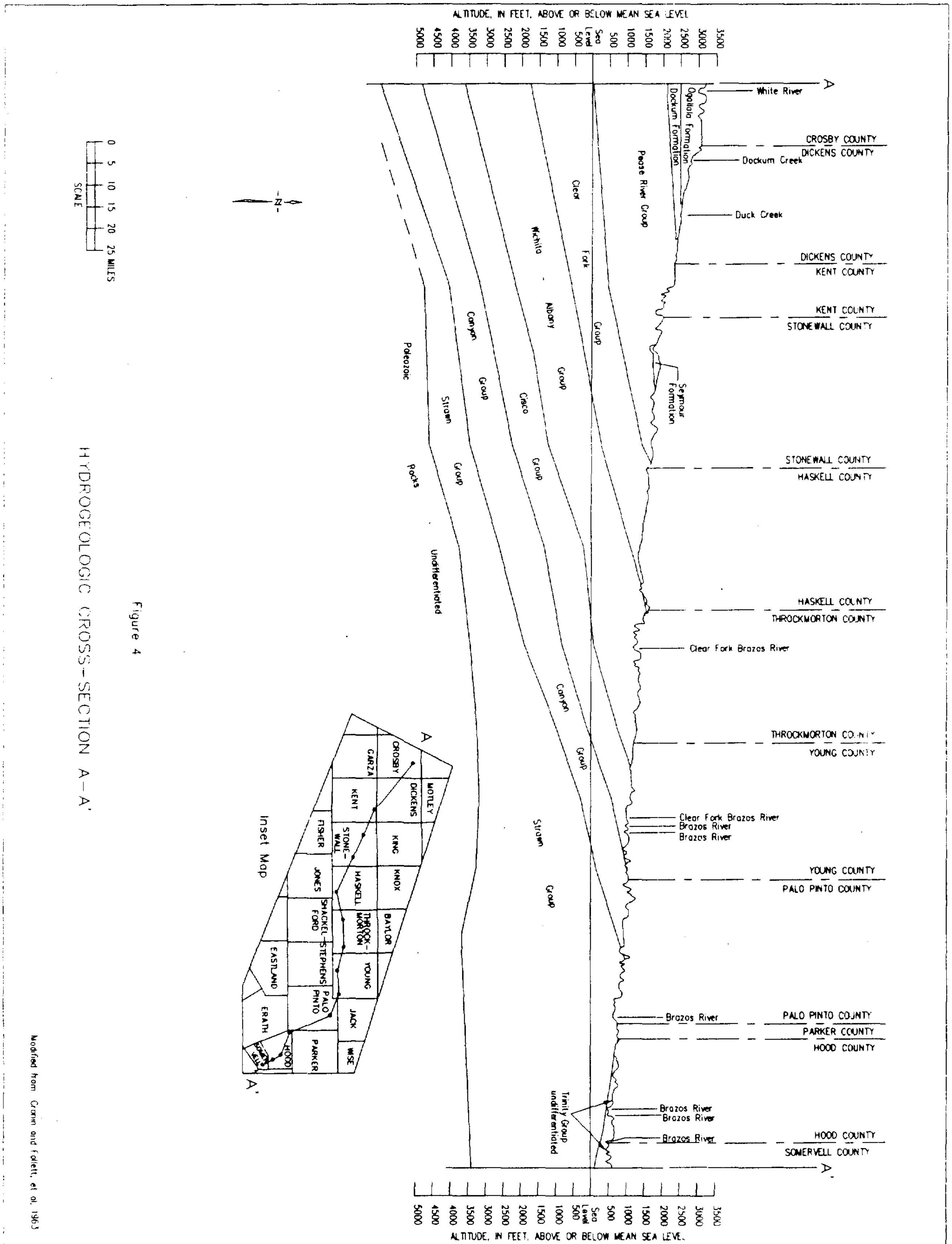


Figure 4

HYDROGEOLOGIC CROSS-SECTION A-A'

The formations of the Cisco Group of Late Pennsylvanian age crop out in a northeastward-trending belt which ranges about 8 to 40 miles wide and includes parts of Callahan, Eastland, Stephens, Shackelford, Throckmorton, Young, Jack, and Archer Counties. The Cisco Group, consisting of shale, sandstone, limestone, conglomerate, and beds of coal, is probably the most productive of the Pennsylvanian rocks in the study area. The aquifer yields small supplies of fresh to slightly saline water to numerous domestic and livestock wells and a few public supply and industrial wells. Most of the industrial wells are used for water-flood use in secondary recovery of hydrocarbons (oil and gas).

The formations of the Wichita-Albany Group of the Early Permian, crop out in parts of Callahan, Taylor, Shackelford, Jones, Haskell, Throckmorton, Baylor, Archer, Wichita, Clay, and Montague Counties in a general northerly direction to form a belt ranging in width from about 8 to 20 miles. The formations within the group consist of limestone, sandstone, siltstone, conglomerate, and coal. Water wells in the Wichita-Albany Group are of low yield and commonly do not provide an adequate supply as most wells cannot sustain prolonged pumpage. The water is used for domestic and livestock purposes, but poor quality in some places precludes use for human consumption.

The formations of the Clear Fork Group of Permian (Leonardian) age crop out in a north-south directional about 30 to 35 miles wide and extend through Taylor, Jones, Haskell, Knox, Foard, Baylor, and Wilbarger Counties. These formations consist of shale and thin layers of limestone, dolomite, gypsum, marl, and sandstone. The Clear Fork Group generally yields small quantities of water for domestic and livestock use, however, in Jones County, small to moderate quantities of water are used for irrigation and industrial use.

The formations of the undifferentiated Pease River/Whitehorse Groups of Late Permian age crop out in a north-south direction as shown in Figure 3. The Pease River Group consists of shale, anhydrite, gypsum, limestone, dolomite, and sandstone. Brine springs issuing from formations in the Pease River Group with sodium and chloride contaminate the major rivers and tributaries that flow through the study area.

The Blaine Formation of the Pease River Group, consisting of gypsum and anhydrite, is the most prolific aquifer within the Group and is designated as a minor aquifer of the state. The Blaine extends in a narrow outcrop band from Wheeler to King Counties, as shown on Figure 3. Beyond King County, southward to Coke County, the aquifer locally contributes only a minor amount of water. The Blaine will be discussed in more detail in other sections of the report.

The primary source of ground water in the Blaine is precipitation that falls on the outcrop. The solution openings and fractures in the gypsum offer easy access for the water to percolate downward. The Blaine also may receive some of its recharge from the overlying Dog Creek Shale.

Ground water occurs chiefly in solution channels and caverns in beds of anhydrite and gypsum. In most places the water occurs under water-table conditions; however, in some areas it is confined by relatively impervious beds within the Blaine. The aquifer is also artesian where overlain by the Dog Creek Shale. Because of differential solution in the subsurface, it is common for dry holes or wells of low yield to be found adjacent to wells of moderate to high yields.

The Whitehorse Group, the youngest of the Permian system, crops out in a north-south direction near the western edge of the Rolling Prairie Region as shown in Figure 3. The formations in the Group consist of interbedded shale, siltstone, and fine- to coarse-grained sandstone with thin beds of gypsum, anhydrite, and dolomite in the lower part. Wells yield small to moderate quantities of fresh to moderately saline water for public supply, irrigation, domestic, and livestock use.

The Triassic rocks of the Dockum Formation are exposed along the eastern escarpment of the High Plains, in the Canadian River "breaks",and in outcrops of limited areal extent from Mitchell County northward into Armstrong County as shown in Figure 3. The Dockum designated as a minor aquifer, can be subdivided into two or three formations depending on the location. A basal member, the Tecovas consists of variegated shales and clays, sometimes sandy or silty. Tecovas beds are not known to yield water to wells. The middle unit, the Santa Rosa Sandstone, consists of fine- to coarse-grained sandstone and conglomerate with interbedded shale and clay. In the northern part of the Panhandle, the Trujillo Member is approximately equivalent to the Santa Rosa Sandstone and yields small to moderate amounts of water in locally developed areas. The Santa Rosa is the major water-bearing unit of the Triassic. The upper unit is the Chinle Member and consists of red, blue, and reddish-brown clays and shales which yield small quantities of water to domestic and livestock wells.

The primary source of ground water in the Dockum Formation is the precipitation on the outcrop. Locally, the amount of replenishment depends on the permeability of the outcropping rock or the nature of the soil mantle and vegetative cover. Regionally, the amount fluctuates with variation in precipitation. Water in the outcrop area is unconfined and, therefore, under water-table conditions. Downdip from the outcrop, the water is confined under hydrostatic pressure and is under artesian conditions.

The Seymour Formation (Quaternary), designated a major aquifer, consists of isolated areas of alluvium which occur in parts of twenty-two north-central counties in the study area (Figure 3). Ground water in the Seymour occurs in unconsolidated sediments consisting principally of discontinuous beds of poorly sorted gravel, conglomerate, sand, silty clay, and caliche. The sediments were deposited by streams flowing generally eastward and mostly represent material eroded from the High Plains. Individual areas vary greatly in thickness, with a total thickness of usually less than 100 feet; however, in isolated areas in the northern part of the aquifer, thickness may reach 360 feet from the filling of paleokarst features.

Saturated thickness of the Seymour is commonly less than 100 feet, and in the northern part of the study area is commonly less than 50 feet. Total saturated thickness of these deposits are directly related to the amount of erosional dissection from drainage development across these remnants, with increased dissection resulting in increased drainage of the water bearing units and decreased saturated thickness. The upper portion of the Seymour is typically composed of fine-grained, well-cemented sediments. It contains much stored water but does not readily transmit this water. The important difference between these materials and those generally found in the lower part of the Seymour is that the basal portion of the formation has greater permeability. It is for this reason that greater volumes of water are produced from the basal part of the formation.

Direct infiltration of precipitation is the method by which nearly all recharge occurs to the Seymour. The water is unconfined in the Seymour and is, therefore, under water-table conditions. In most areas, the level of the water table is above the top of the basal sands and gravels.

The youngest rocks exposed in the study area are the alluvial and eolian deposits of Quaternary age. The alluvium consists of floodplain and channel deposits composed of fine sand, silt, clay, and gravel. Small amounts of alluvium are found along almost all streams in the study area. The channel deposits are of hydrologic significance within the valleys of the Red and Pease Rivers where the deposits reach a maximum thickness of 50 feet. The most favorable sediments for development are the more permeable deposits which can be found in oxbows of former streambeds.

The terrace deposits are an important source of fresh water for municipal, domestic and irrigation use. The alluviums are found along major streams, while the terrace deposits of similar origin are deposited at higher elevations.

Floodplain deposits are derived, for the most part, from the Seymour Formation and were transported to their present position by existing streams. These sediments were erratically deposited and are very discontinuous. They vary in thickness from 30 feet to 60 feet. Because porosities and permeabilities vary greatly, well yields also range from small to moderate.

Recent alluvium deposits lie unconformably on the Seymour Formation resulting in hydrologic communication between the two. Locally there may be drainage from these deposits into more porous Permian beds below.

Water produced from the Recent alluvium is typically from shallow wells. The quality of the water in the alluvium ranges from fresh to moderately saline. Much of the water is high in sulfate content.

Recharge, Movement, and Discharge

Recharge to the Blaine Formation occurs by infiltration of precipitation on the High Plains escarpment and Permian strata to the west and on the Blaine outcrop. In Hardeman County, the estimated amount of recharge to the Blaine Formation from direct infiltration of precipitation is from 5 to 7 percent of the amount of precipitation (Maderak, 1972). The annual effective recharge to the entire Blaine Formation is estimated to be 142,600 acre-feet (TDWR, 1984).

Water in the Blaine moves eastward along solution channels and caverns, dissolving the evaporitic deposits and discharging into topographically low areas through salt seeps and springs. Artificial discharge is from wells in the heavily irrigated areas. In 1988, the estimated amount of ground water pumped for all uses from the Blaine was approximately 7,300 acre-feet.

The annual effective recharge to the Dockum aquifer in the study area is approximately 15,000 acre-feet (TDWR, 1984). The movement of water follows a west-southwest direction from the outcrop, generally paralleling the dip of the beds. The hydraulic gradient ranges from a maximum of 200 feet per mile in northeastern Floyd County to 25 feet per mile in Nolan County. Ground water is discharged naturally from springs and seeps wherever the water table is within a few feet of the land surface. Dockum ground water is discharged artificially through wells with approximately 5,400 acre-feet pumped in 1988 for all uses.

Direct infiltration of precipitation on the land surface is the method by which nearly all recharge to the Seymour aquifer occurs. Surface streams adjoining the Seymour outcrop are at elevations lower than water levels in the Seymour aquifer and cannot contribute to the Seymour. Some water pumped for irrigation and municipal use infiltrates and returns to the aquifer, but these amounts are relatively small. The only other possible source of recharge to the Seymour is upward leakage from underlying Permian formations. This probably occurs in some areas, but amounts are small and insignificant. Recharge from precipitation is not uniform over the study area. Considerably more recharge occurs in the sand hills area and in other areas where the land surface consists of sand materials. The annual effective recharge to the Seymour is approximately 207,200 acre-feet (TDWR, 1984).

The movement of ground water is down-gradient, from high to low elevations, at right angles to the contours which denote the configuration of the water table. The ground-water movement is generally toward the major streams or their tributaries. Hardin (1978) estimated that in Haskell County the average rate of ground-water movement in the Seymour is typically between 800 to 1,200 feet per year.

Natural discharge from the Seymour occurs through seeps and springs, evapotranspiration by plants, evaporation from the water table, and leakage to the Permian. Seeps and springs occur along the edges of the aquifer. Hardin (1978) estimated that the total ground water discharge by evapotranspiration is a large part of the total natural discharge from the aquifer and is considerably larger than from the springs and seeps. Leakage from the Seymour to the underlying Permian rocks is very small due to the geologic character of the Permian. Ground water discharged by wells in 1988 from the Seymour aquifer amounted to approximately 108,600 acre-feet.

Hydraulic Characteristics

Water producing capabilities of an aquifer depend upon its ability to recharge, transmit, and store water. Not all water in storage is recoverable by pumping because of the molecular attraction between rock particles and water molecules. Formulas have been developed to show the relationship of the yield of a well and shape and extent of the cone of depression to the properties of the aquifer, including specific yield, coefficients of transmissibility and storage, and permeability.

The coefficient of transmissibility is a measure of the amount of water that will move through an aquifer and is expressed typically in gallons per day per foot (gpd/ft). Permeability is the capacity for transmitting a fluid. It is equal to the transmissibility divided by the thickness of the aquifer and is expressed typically in gallons per day per square foot (gpd/ft^2). The coefficient of storage is a measure of the amount of water which is given up from storage in an aquifer when the water level is lowered. In an unconfined aquifer under water-table conditions, the coefficient of storage is equal to the specific yield.

The hydraulic properties of the Blaine are generally undetermined due to lack of sufficient data. The seemingly random occurrence of solution channels in the Blaine aquifer makes it difficult to determine transmissibilities and permeabilities in any given area. The Blaine aquifer has water-soluble rocks that characteristically have a wide range in water-transmission properties. The Blaine Formation is permeable locally, and high yields are obtained in these places such as in western Hardeman and in parts of Collingsworth and Childress Counties. However, even in areas where yields are generally high, yields of a particular well may be low. Data available from wells completed in the Blaine in Collingsworth County have a range of specific capacities from 7 to 20 gallons per minute (gpm) per foot of drawdown to an average of 47 gpm per foot of drawdown in Childress County.

Test results reported by Shamburger (1967) in Mitchell County on the lower Santa Rosa Sandstone (Dockum Formation) from four wells having yields of 70 to 245 gpm indicate an average coefficient of transmissibility of 8,845 gpd/ft and a coefficient of storage of 0.00019. Because the wells tested included none with large yields, the average coefficient of transmissibility determined is probably low.

The following taken from TWDB Reports 218 and 161, and TDWR Reports 226, 215, and 240 lists the coefficients of transmissibility, storage, and permeability from pumping tests of Seymour wells within the study area:

County	Average Coefficient of Transmissibility (gpd/ft)	Range of Coefficient of Permeability (gpd/ft^2)	Average Coefficient of Storage
Baylor	50,000	790–2,000	0.11
Hardeman	25,000	——	——
Haskell	115,000	1,200–17,000	0.15
Jones	55,000	1,220–4,690	0.11– 0.18
Knox	75,000	900–13,600	0.15
Wilbarger	40,000	——	0.14

The wide range in values indicates a non-uniform aquifer which varies greatly in hydraulic character. This variance is typical of an aquifer with the geologic character of the Seymour.

Water-Level Fluctuations

The discharge from wells and recharge from precipitation are the most important factors controlling the changes in water levels. The magnitude of the change in a particular well depends mainly on the proximity of the measured well to an area of discharge or recharge, and to some extent on the lithology of the water-bearing unit. Figures 5, 6, and 7 illustrate water-level fluctuations in the Blaine, Dockum, and Seymour aquifers in the study area. The hydrographs, in general, reflect noticeable changes in water levels which correspond to changes in rainfall and public supply or irrigation pumpage.

Data available for the period 1953 to 1990 for the Blaine aquifer indicate that few definite trends in water levels can be determined (Figure 5). The changes in water levels in the Blaine from 1953 to 1990 ranged from a rise of between 2 and 16 feet to a decline of 3 feet. During the period 1962 to 1975, water levels in selected wells experienced a net decline of 10 to 23 feet.

Data from selected wells in the Dockum Formation show a rise in water levels of 12 to 36 feet over the period of record (Figure 6). The rises have ranged between 0.5 to 1 foot per year from 1954 to 1990.

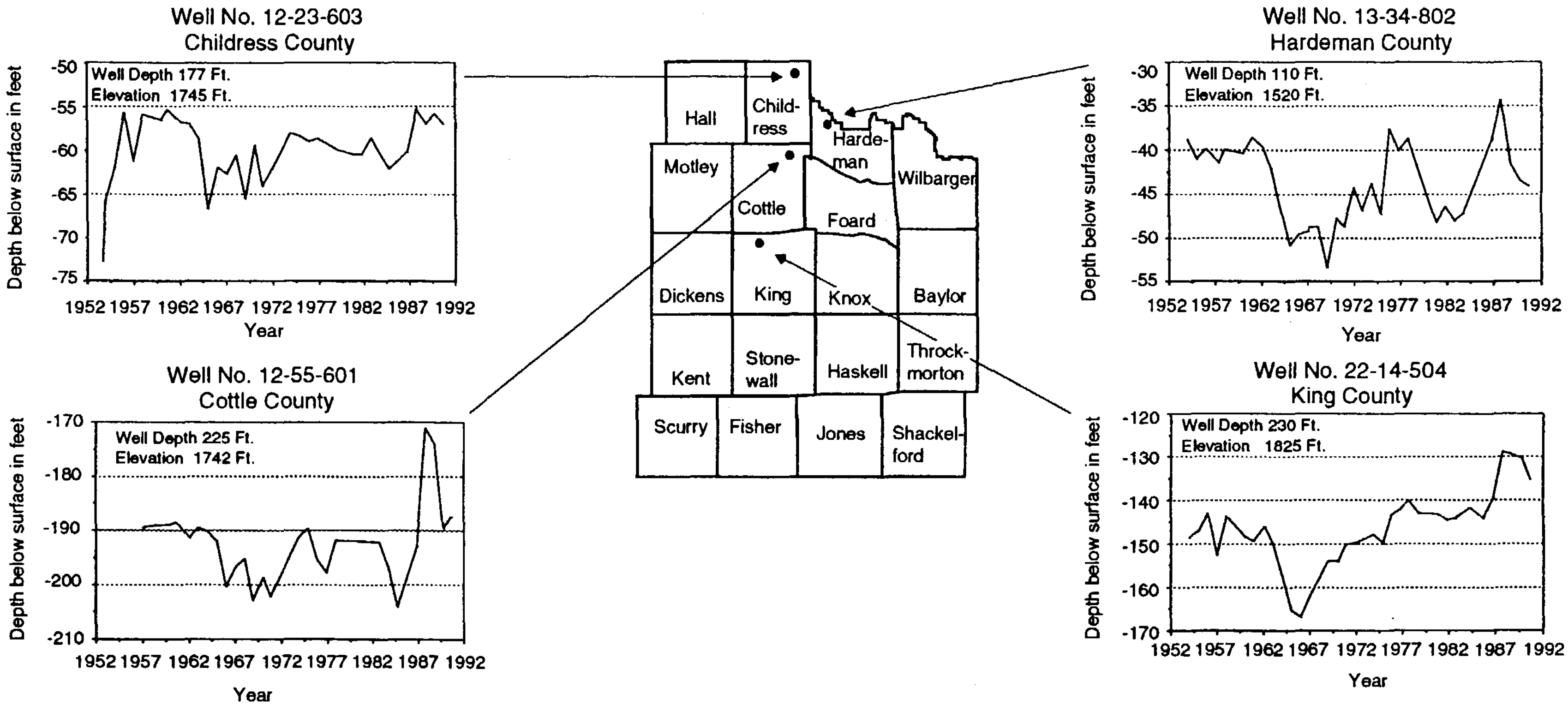


FIGURE 5
HYDROGRAPHS OF SELECTED WELLS IN THE BLAINE AQUIFER OF THE PEASE RIVER GROUP

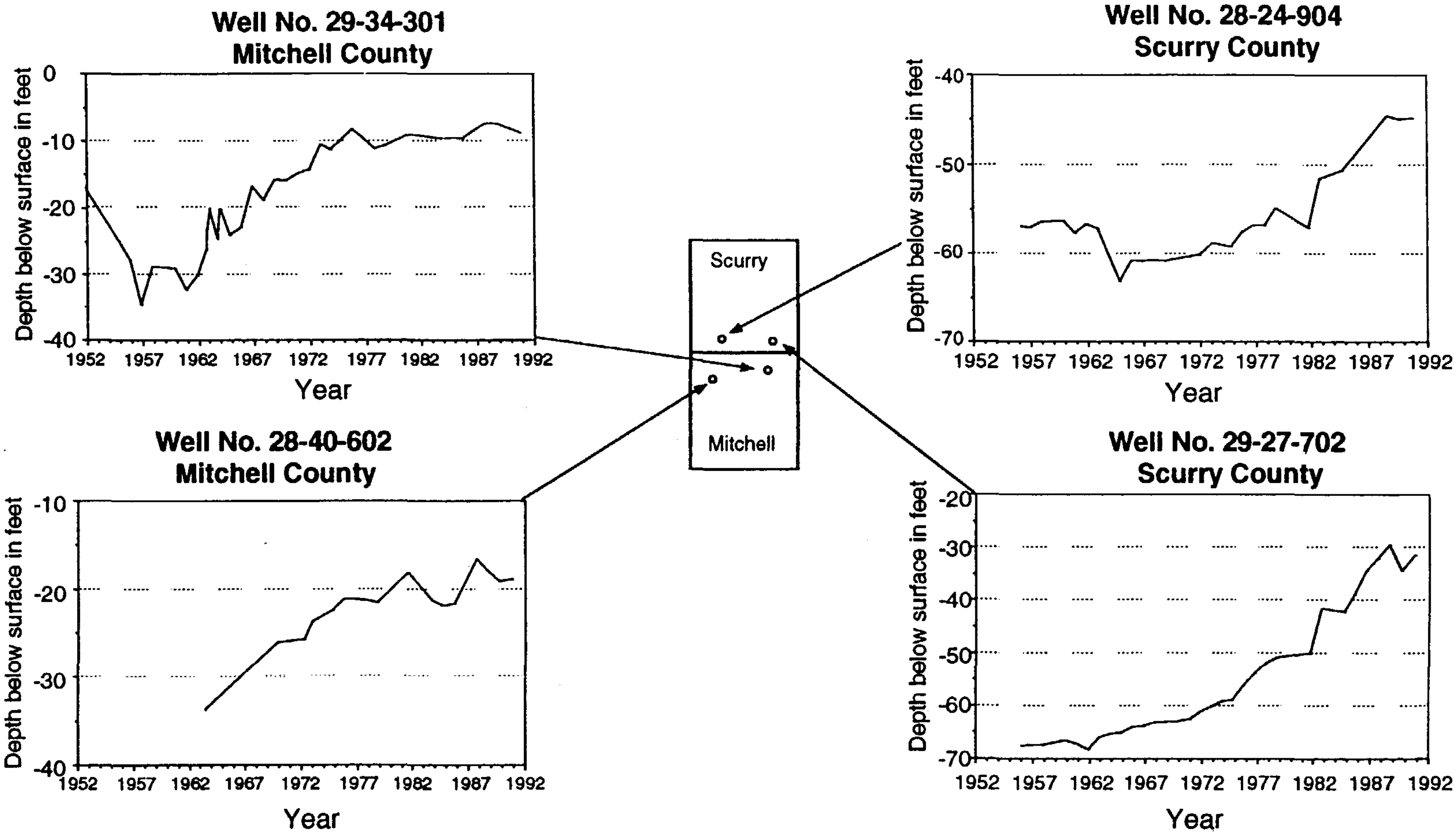


FIGURE 6
HYDROGRAPHS OF SELECTED WELLS IN THE DOCKUM FORMATION

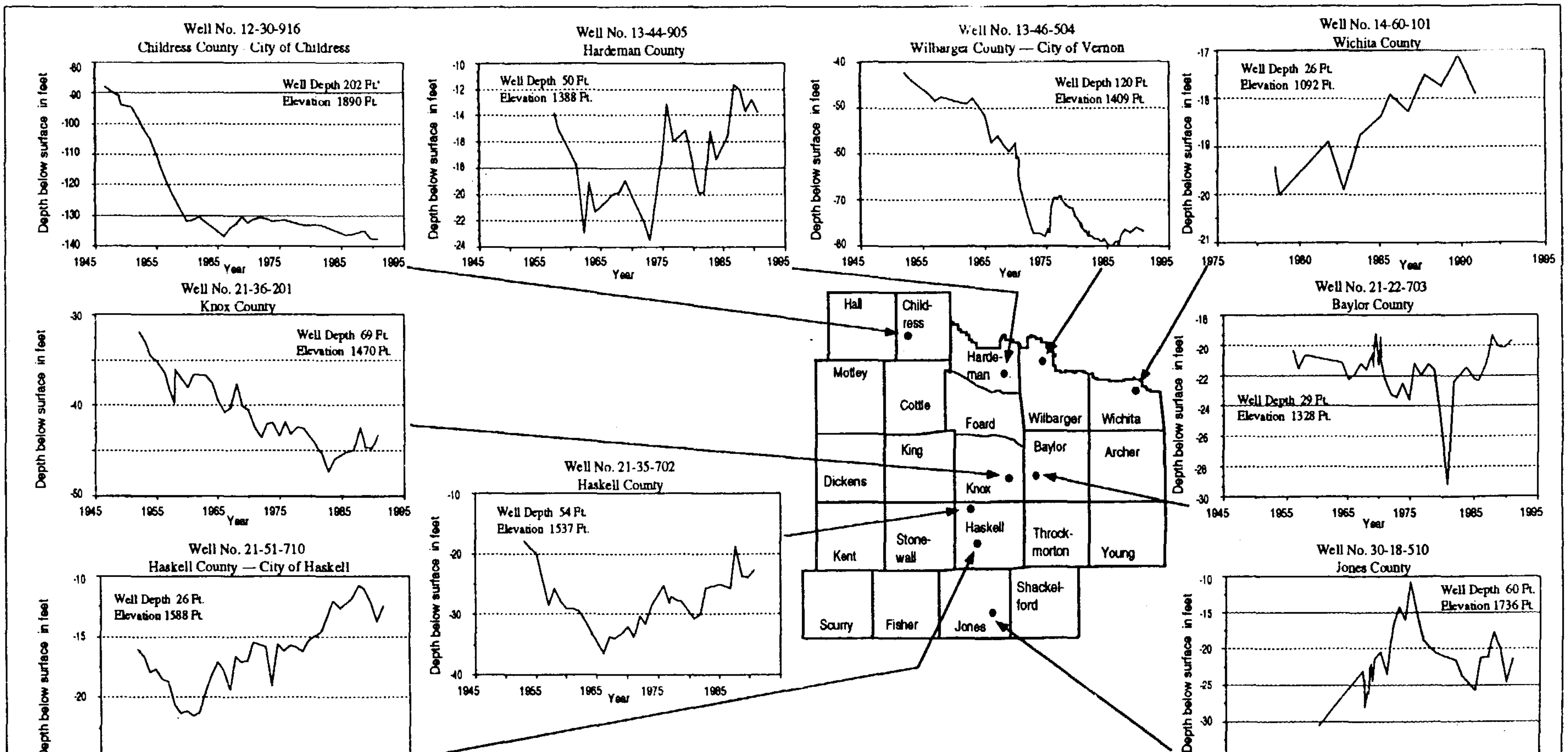


FIGURE 7
HYDROGRAPHS OF SELECTED WELLS IN THE SEYMOUR AQUIFER

Data from selected wells for the Seymour aquifer are shown in Figure 7. The hydrographs for wells located in the Cities of Childress (12-30-916) and Vernon (12-46-504) show the greatest declines in water level with the City of Childress experiencing a 1.1 foot per year decline from 1946 to 1990. Other hydrographs of Seymour wells in the study area show a water-level rise and a noticeable seasonal change in water levels which correspond to changes in rainfall and irrigation pumpage. The peak water levels generally occur during March, April, May, and June which coincide with increased rainfall and decreased pumpage. There is an overall decline in water levels during the growing season and the hot summer months as a result of irrigation pumpage.

Chemical Quality

The chemical character of ground water mirrors the mineral composition of the rocks through which it has passed. As water moves through its environment, it dissolves some of the minerals from the surrounding rocks. Concentrations of the various dissolved mineral constituents depend upon the solubility of the minerals in the formation, the length of time the water is in contact with the rock, and the concentration of carbon dioxide present within the water. Dissolved mineral concentrations generally increase with depth and temperature. Neutralizing or removing undesirable constituents is usually difficult and can be expensive.

The primary limiting factor of ground water use is the total dissolved-solids concentration (TDS). The Texas Ground Water Protection Committee in 1991 established a classification system for ground water based on TDS: fresh is defined as 0 to 1,000 mg/l; slightly saline is defined as more than 1,000 to 3,000 mg/l; moderately saline is defined as more than 3,000 to 10,000 mg/l; and very saline to brine is defined as more than 10,000 mg/l.

TWDB analyses report a dissolved solids value which is calculated from the sum of the constituents as analyzed in the laboratory. True TDS is normally calculated from the specific conductance of the water. However, since the difference between these numbers is generally less than 2%, and the field conductivity meter is not as accurate, the TWDB value can be considered equal to TDS.

Numerous reports describe the ground water quality in the study area. The more important reports listing the aquifer, county, and referenced reports are as follows:

Blaine Aquifer
Childress (Shafer, 1957); Collingsworth (Smith, 1970); Hall and Briscoe (Popkin, 1973b); Hardeman (Maderak, 1972); Jones (Price, 1978); Ground-water Quality of Texas (TWC 89-01).

Dockum Aquifer
Dickens and Kent (Cronin, 1972); Mitchell and Nolan (Shamburger, 1967); Motley and Floyd (Smith, 1973); Hall and Briscoe (Popkin, 1973b); Ground-water Quality of Texas (TWC 89-01).

Seymour Aquifer
Baylor (Preston, 1978); Childress (Shafer, 1957); Collingsworth (Smith, 1970); Dickens and Kent (Cronin, 1972); Hall and Briscoe (Popkin, 1973b); Hardeman (Maderak, 1972); Haskell and Knox (Hardin, 1978 & Ogilbee & Osborne, 1962); Jones (Price, 1978); Motley (Smith, 1973); Wilbarger (Price, 1979); Ground-water Quality of Texas (TWC 89-01).

Dissolved solids concentration in the Blaine aquifer increases with the depth from the surface to the west and in natural discharge areas. Fresh water occurs in topographically higher (recharge) areas in the outcrop, and may be enhanced by recharge from overlying alluvium (Figure 8). Increased TDS content can make the water unsuitable for drinking and irrigation.

A recognized ground-water problem in the Blaine is the natural pollution of surface water from ground water issuing from salt springs and seeps. Richter and Kreitler (1986) modelled two separate hydrodynamic systems separated by the evaporite section of the Pease River and Clear Fork Groups: (1) a shallow upper aquifer which receives recharge within the High Plains and the Rolling Plains, flows eastward, and dissolves updip sections of halite-bearing formations, and (2) a lower deep-basin aquifer, which receives recharge in central New Mexico, traverses the High Plains below the Permian salt section, and flows generally to the east and northeast. The upper aquifer includes the Seymour aquifer and Dockum Formation down to the halite-dissolution zones in the Pease River and Clear Fork Groups. The lower aquifer includes the Wichita-Albany, Cisco, Canyon, and Strawn Groups (Table 1).

As a result of the hydrodynamics of the upper aquifer and the Permian evaporite, numerous natural salt springs and seeps occur throughout the Pease River and Clear Fork Groups in a north-south trend in the Rolling Plains to the east of the High Plains Escarpment. Salt flats occur at these major brine discharge points. Tributaries of the Red and Brazos Rivers which have their headwaters along these outcrops have high chloride and dissolved- solids contents (Figure 9).

The hydraulic head of the lower aquifer in most localities is the same as or greater than the shallow aquifer, which could force the water from the lower aquifer to move vertically toward the surface if a pathway exists. Such a pathway may be natural, such as a fault or fracture, or manmade, such as a water or oil well. Water from wells and springs completed in the lower portion of the Blaine Formation is calcium-magnesium, sulfate ion dominated.

Water from the Blaine Formation is usually very hard and the dissolved-solids content ranges from 1,000 to over 10,000 mg/l, and some wells in the Blaine have high concentrations of sodium and chloride. The high sulfate content of the ground water is in excess of TDH Standards for municipal use. In general, the water from the Blaine is too mineralized for most industrial uses.

Although water has been used successfully for irrigation for many years, under unfavorable soil and slope conditions some of the ground water may not be suitable for irrigation because of medium sodium hazard (SAR) and very high salinity hazard. Winslow and Kister (1956) found that in Childress County some of the water analyzed contained up to four parts per million of boron. This range of boron could cause severe crop toxicity problems.

Dissolved-solids content in the Dockum Formation ground water varies from less than 500 mg/l to over 10,000 mg/l (Figure 10). The majority of the pumpage from the aquifer is used for municipal, irrigation, and oil field water-flooding purposes. A basinward increase in TDS concentration may be due to the lack of recharge water entering the basin and/or decreasing permeability which allows a longer time for ground water to dissolve the surrounding rock matrix. Dutton and Simpkins (1986) also indicated the

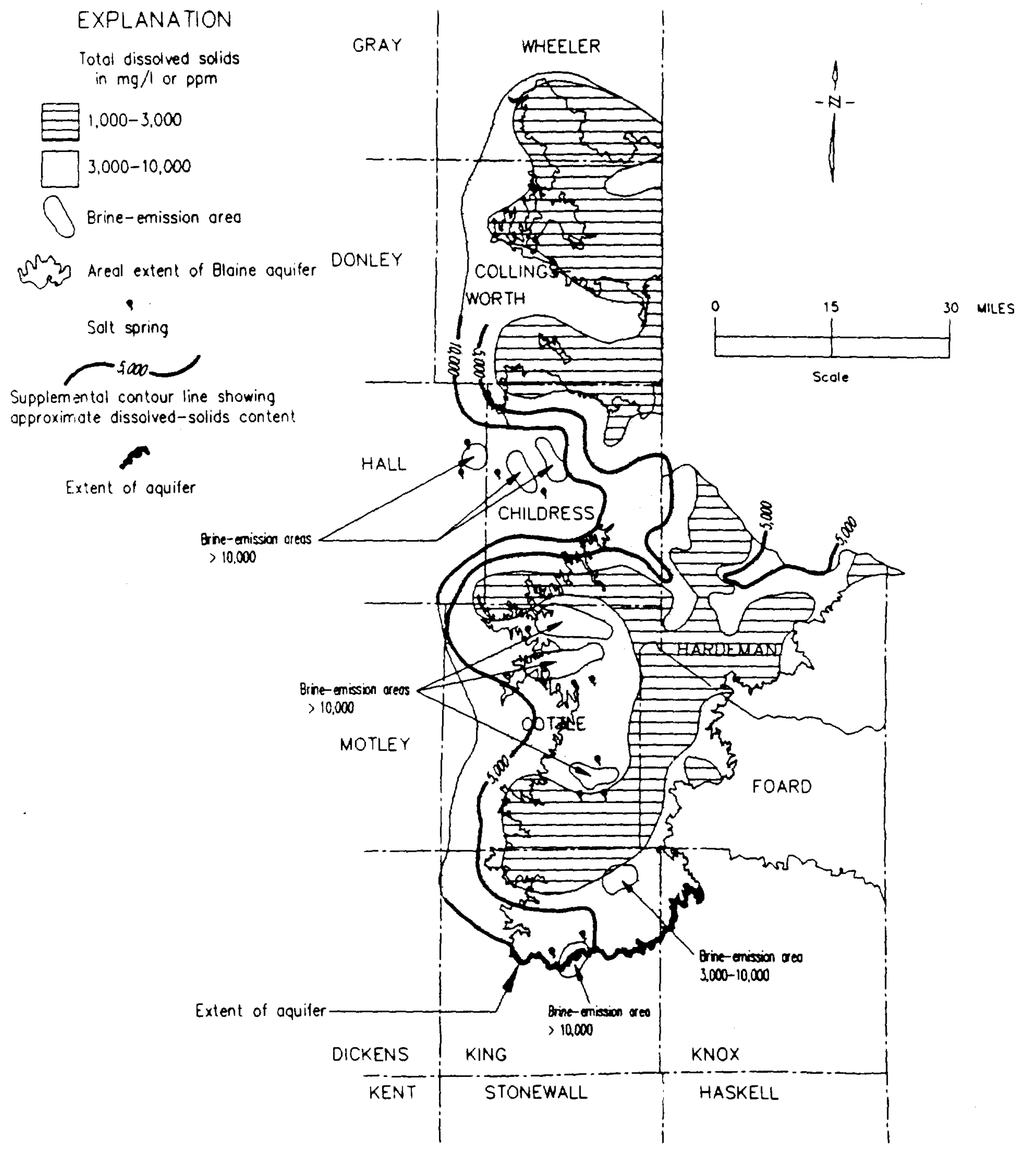


Figure 8

HISTORICAL GROUND-WATER QUALITY IN THE BLAINE FORMATION OF THE PEASE RIVER GROUP

Modified from: Texas Water Commission Report 89-01 Figure 23

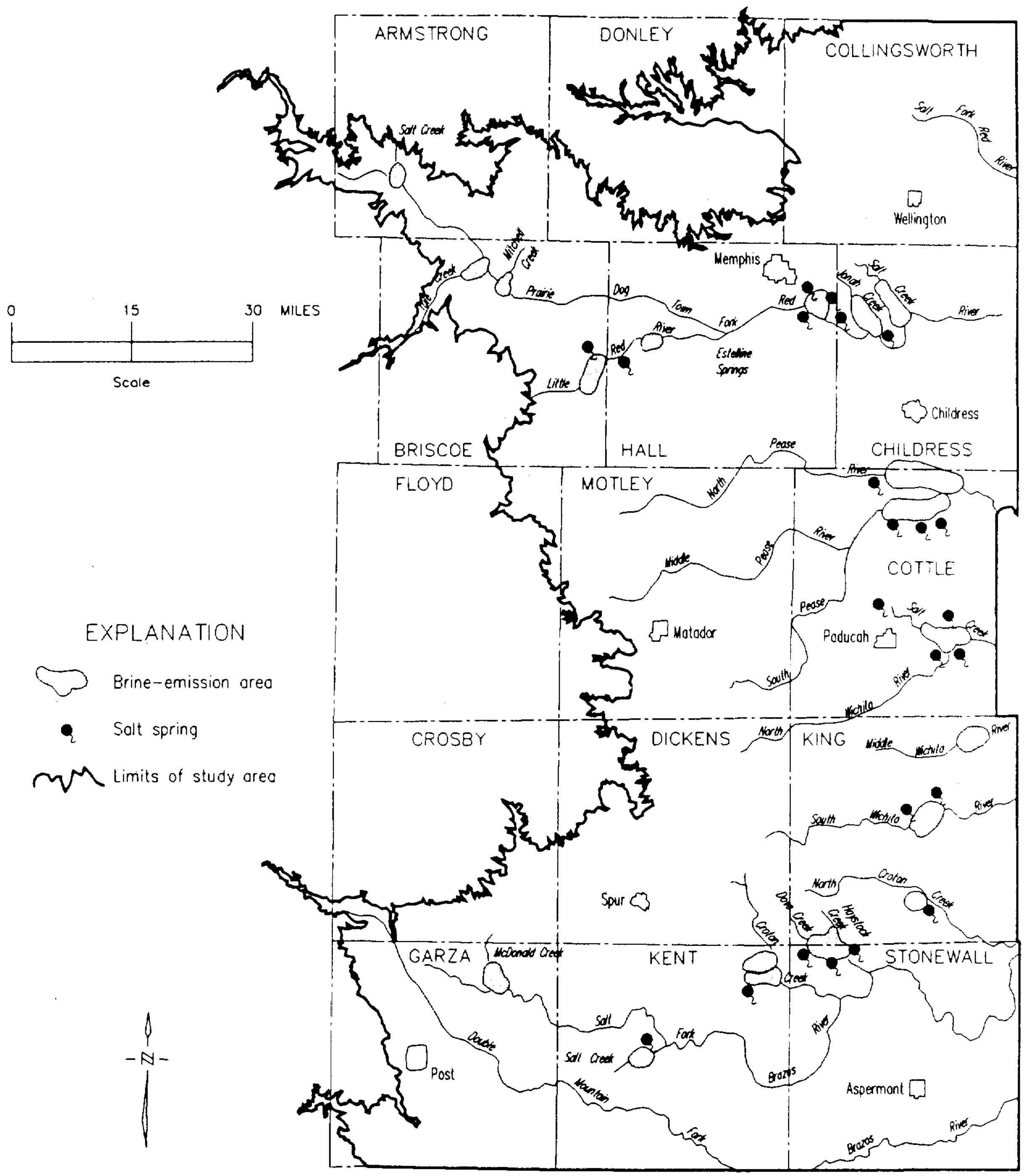


Figure 9

LOCATION OF NATURAL BRINE-EMISSION
AREAS AND SALT SEEPS

Modified from: BEG, Rpt.of Inv. No. 155, 1986, Fig.1

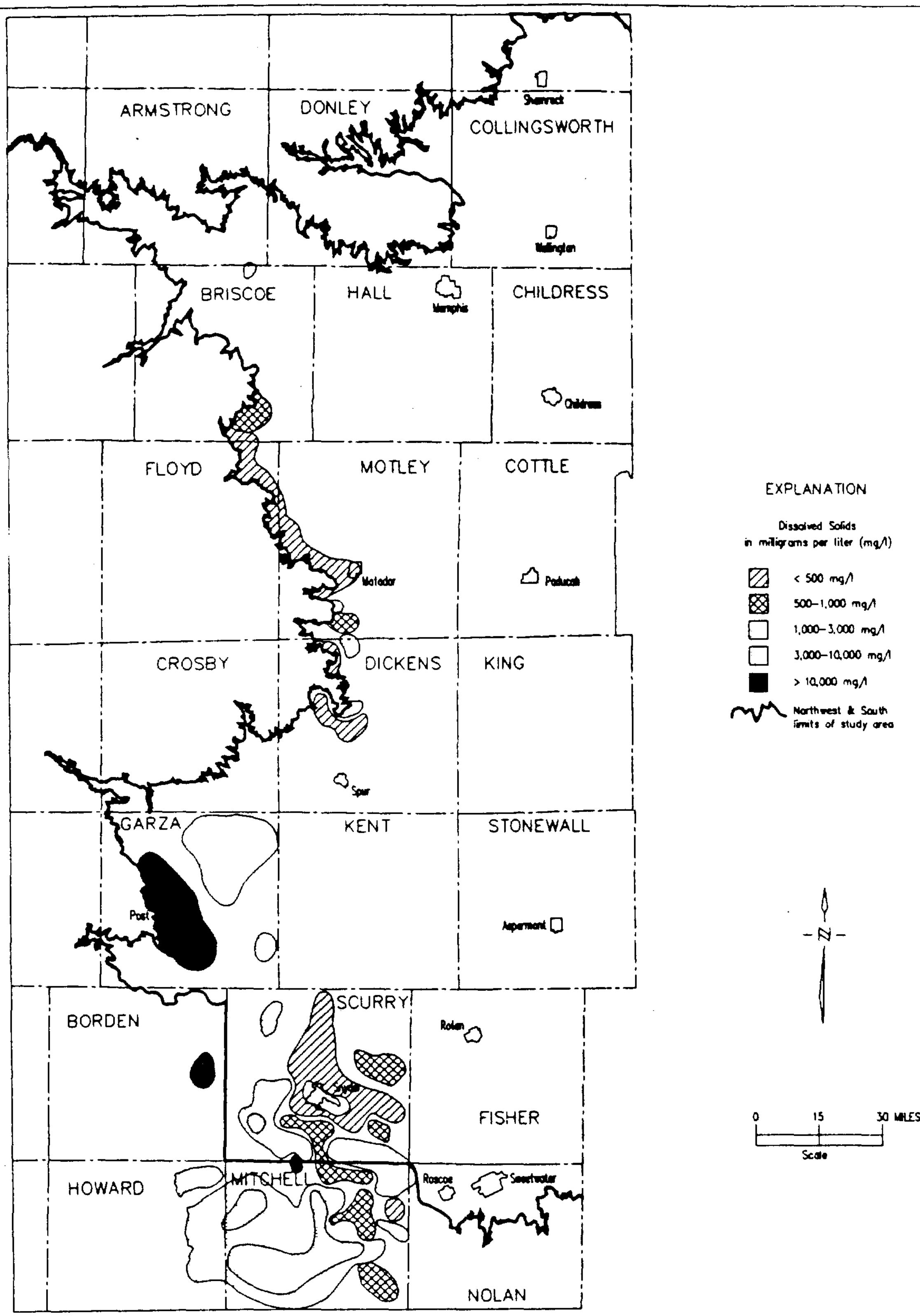


Figure 10

HISTORICAL GROUND-WATER QUALITY IN THE DOCKUM FORMATION increased dissolved-solids content may be due to the inflow and mixing of ground water that has dissolved halite from the underlying Permian.

Shamburger (1967) reported that ground water from the "Santa Rosa" aquifer in Mitchell and Nolan Counties is useable for municipal and most irrigation and industrial uses. Hardness, however, is very high and fluoride content marginally acceptable.

Water quality in the Seymour aquifer is variable throughout the study area (Figure 11). R.W. Harden and Associates (1978) indicated that lower TDS content in Haskell and Knox Counties could be correlated with recharge areas having sandy soil. High TDS including high chloride concentrations that occur away from recharge areas may represent natural mineralization from rock-water interaction or from Permian strata. Whether the high chloride content in the aquifer is natural or man-induced, such as from oil-field brines or septic tanks, is difficult to determine on a regional basis. In some areas the salinity of the Seymour has increased with pumping to the point that the water has become unsuitable for domestic and municipal uses.

The sulfate content of the Seymour aquifer varies greatly throughout the study area and often exceeds the secondary drinking water standard of 300 mg/l. Concentrations of sulfate in excess of the recommended amount cause the water to have a disagreeable taste. Much of the sulfate may have been derived from the Permian rocks with which the Seymour is in contact.

Abnormally high nitrate concentrations occur in ground water over a wide geographic area, especially in Haskell and Knox Counties. R.W. Harden and Associates (1978) found a number of widely-scattered domestic and stock wells showing nitrate content in excess of 150 mg/l. Kreitler (1975) indicated the wide-spread distribution of nitrate in ground water may be the result of leaching of soil and humus in agricultural areas once covered by nitrogen mixing vegetation such as grasses and/or mesquite groves. Some of the nitrate in the ground water may be the result of excessive nitrogen fertilizer applied to the soil. Other sources include organic matter attributed to poorly functioning septic systems or infiltration of animal wastes from barnyards.

In addition to natural processes, pollution associated with two important regional industries can also cause deterioration of water quality: (1) inefficient farming practices, and (2) oil-producing operations (Kreitler, 1975).

During the severe drought of the 1950s, many farmers terraced their land in an effort to conserve as much water as possible by altering the natural drainage patterns to prevent runoff and erosion. In the next decade rainfall returned to normal, and the water table began rising, eventually to within a few feet of the surface. Evaporation began which concentrated the salts dissolved in the ground water and caused them to precipitate from the water into the soil. When the next rain event occurred, this salt was dissolved and carried from the original evaporation site to start the process again. Salinization from the evaporation of shallow ground water is a process which can cause water wells to "go bad" and kill vegetation. Other farming practices that can also pollute ground water include the introduction of nitrates from animal waste or septic tanks, excessive application of fertilizers, and misuse of pesticides. All of these pollutants can enter into the ground-water system and affect water quality (Kreitler, 1975).

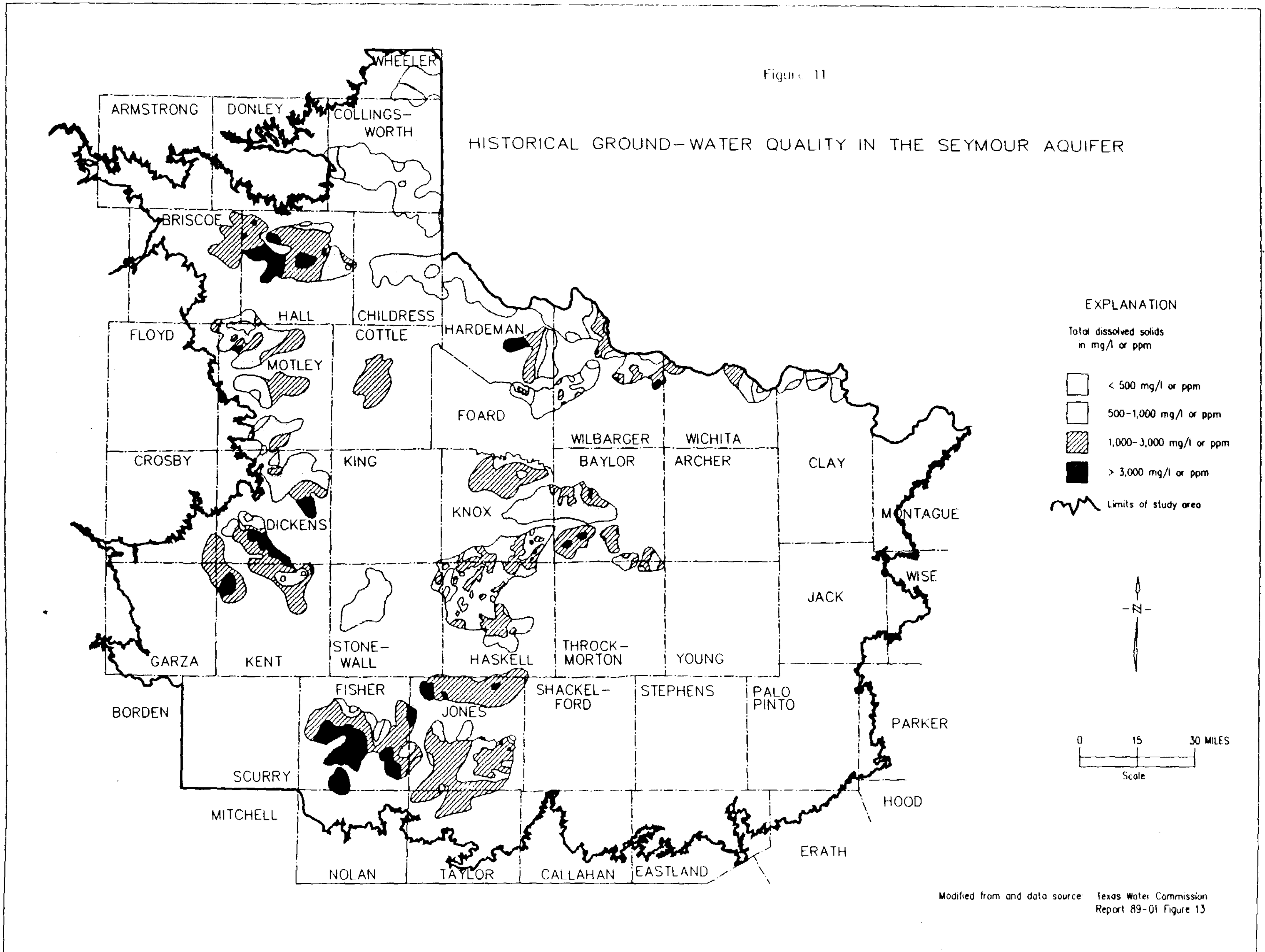


Figure 11

HISTORICAL GROUND-WATER QUALITY IN THE SEYMOUR AQUIFER

Oil-producing operations have been blamed for deteriorating ground-water quality by landowners for many years. Figure 12 shows the locations of oil and gas fields within the study area. Activities which can cause pollution include: (1) leaching of salt beneath abandoned salt-water disposal pits; (2) illegal dumping of produced salt water onto the surrounding land or into surface streams; (3) leaky well casing, either in producing wells or salt-water injection wells; and (4) improperly plugged or abandoned wells, core holes, or shot holes. The location of currently permitted salt-water disposal wells and brine solution mining stations are shown in Figure 13.

Probably the greatest cause of ground-water contamination has been the disposal of oil-field brines into unlined surface pits prior to the statewide "no pit" order of the Railroad Commission of Texas, which became effective on January 1, 1969. In most of the oil fields across the study area, large amounts of brine are produced with oil and gas. The unlined pits facilitated the formation of a "plume" of concentrated brine water which spread into the soil under the pits, contaminated the ground water, and killed vegetation. Today the land surrounding old pits still remains barren of vegetation, and brine has contaminated some water wells (Figure 14).

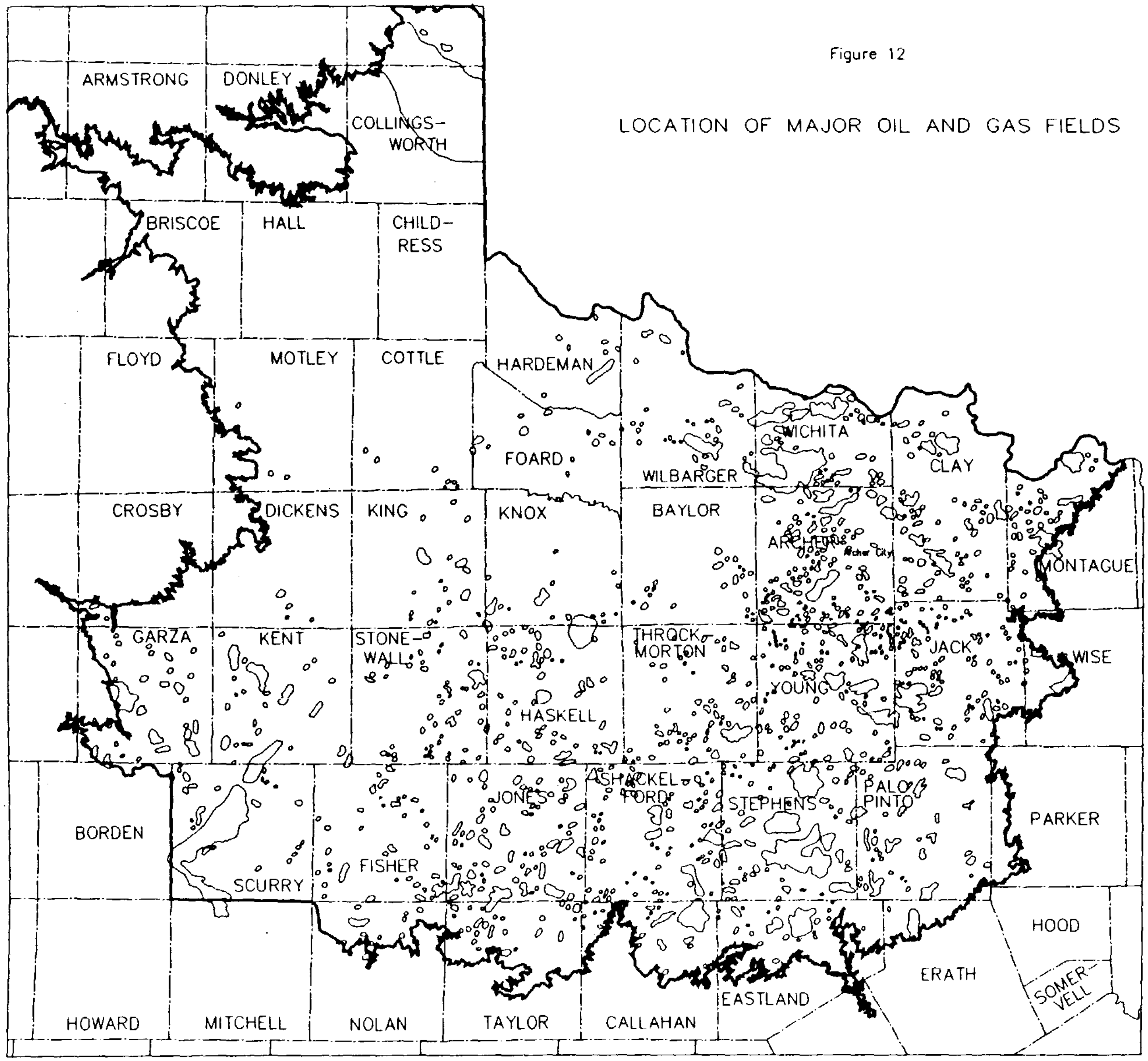
Emergency pit waivers are still granted by the RRC in certain cases (Hall, pers. comm.). In 1985 the permits became more restrictive, and in some geologic areas were banned. Most pits are not required to have liners and may be used only in times of emergency, as when a tank battery is struck by lightning. Placing brine in a pit under such circumstances is preferable to allowing it to run over the ground. Such a pit is not to be used on a regular basis, and the waiver may be revoked if an operator is found to be using a pit in an improper manner.

Producing wells can be sources of pollution if the well casing is corroded or improperly installed. Abandoned water or oil wells, wells which were improperly plugged, or abandoned core holes and seismic shot holes can also serve as pathways for upward-moving brine water to contaminate fresher ground water. Modern salt water disposal wells are a potential source of brine pollution if they are not maintained properly. The RRC requires all wells to be tested periodically for casing leaks to maintain structural integrity.

The large volume of water quality samples examined can be found in a detailed evaluation of the water-quality monitoring in Appendix A of this report.

Figure 12

LOCATION OF MAJOR OIL AND GAS FIELDS



N

0 15 30 MILES
Scale

EXPLANATION

Major Oil and Gas Fields

Limits of study area

Modified from: Energy Resources of Texas 1976, 3rd printing, October 1984
Compiled by Ann E. St. Clair, Thomas J. Evans and L. E. Garner
B.E.G., Univ. of Texas at Austin

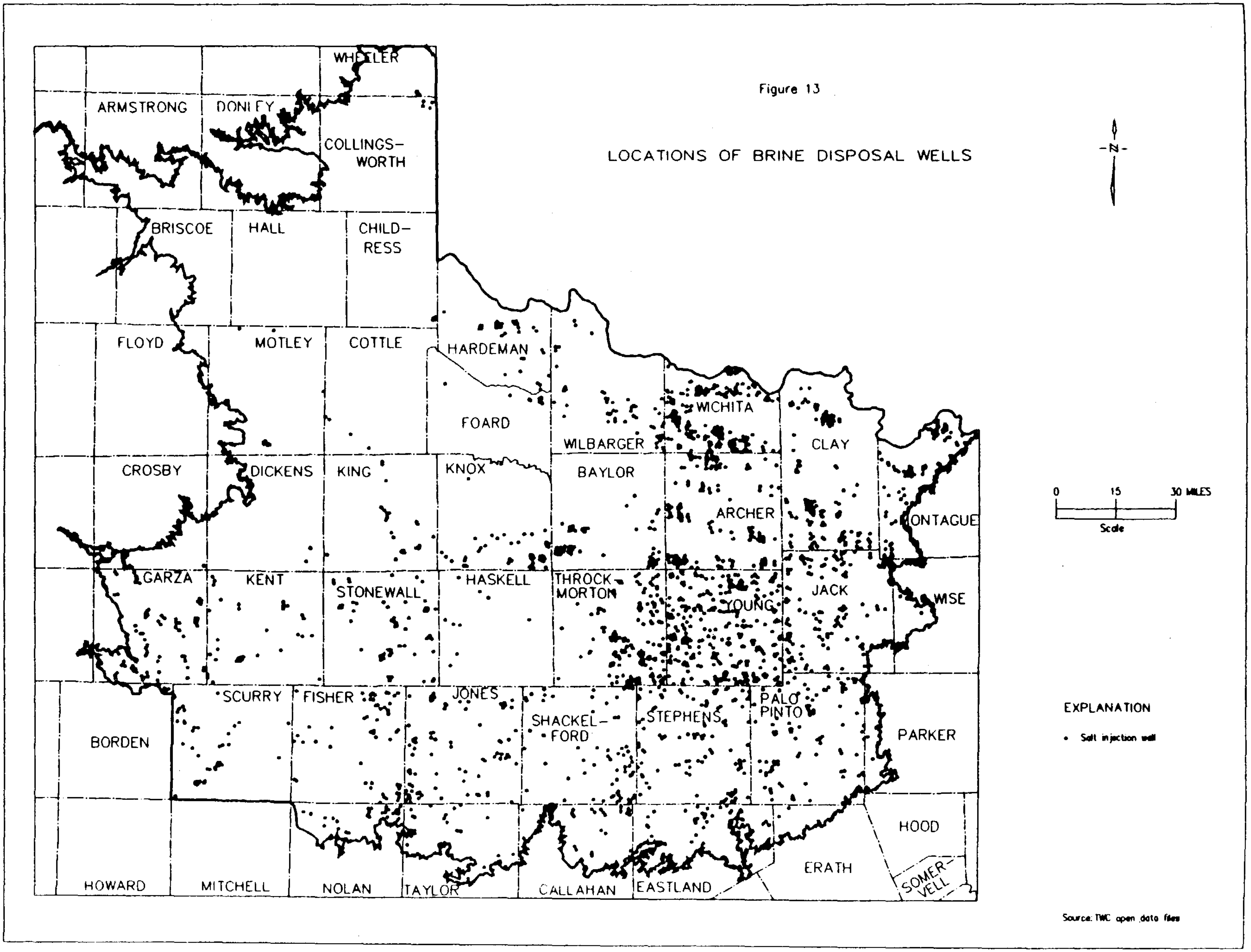
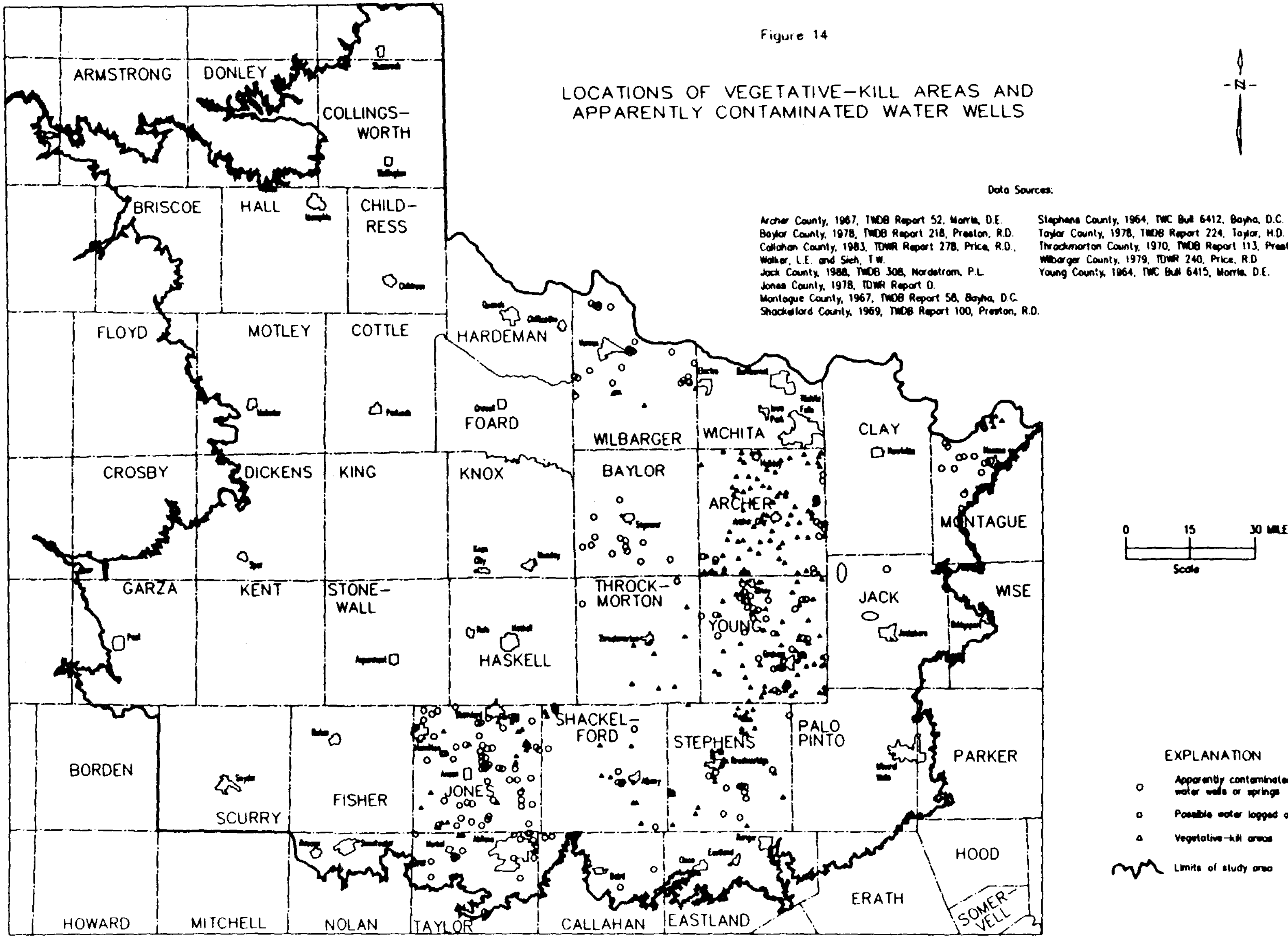


Figure 13

LOCATIONS OF BRINE DISPOSAL WELLS

Figure 14

LOCATIONS OF VEGETATIVE-KILL AREAS AND APPARENTLY CONTAMINATED WATER WELLS



Data Sources:

Archer County, 1967, TWDB Report 52, Morris, D.E.
Baylor County, 1978, TWDB Report 218, Preston, R.D.
Callahan County, 1983, TDWR Report 278, Price, R.D., Walker, L.E. and Sieh, T.W.
Jack County, 1988, TWDB 308, Nordstrom, P.L.
Jones County, 1978, TDWR Report 0.
Montague County, 1967, TWDB Report 58, Bayha, D.C.
Shackelford County, 1969, TWDB Report 100, Preston, R.D.
Stephens County, 1964, TWC Bull 6412, Bayha, D.C.
Taylor County, 1978, TWDB Report 224, Taylor, H.D.
Throckmorton County, 1970, TWDB Report 113, Preston, R.D.
Wilbarger County, 1979, TDWR 240, Price, R.D.
Young County, 1964, TWC Bull 6415, Morris, D.E.

EXPLANATION

- Apparently contaminated water wells or springs
- Possible water logged areas
- Vegetative-kill areas
- Limits of study area

WATER DEMANDS

Population

Based on the most recent statistics of the U.S. Department of Commerce, the region has generally been one of declining population, continuing trends established during the 1970s. There are several reasons for this general decline in population; paramount among these appear to be changes in technology and activity in the petroleum and agri-business sectors. However, increased manufacturing activity in the larger metropolitan areas seems to have provided an influence for stabilization or even an increase in population growth.

The 1980 and 1985 population for cities, rural areas, and counties included in the study area, along with projected estimates for the years 1990, 2000, and 2010, are shown in Table 2. The population of the study area in 1980 was determined from the 1980 census population data gathered by the U.S. Bureau of Census. The percent of area of each enumeration district or census tract lying only partially in the study area was calculated. This percent was applied to the population of the given tract or district to estimate the 1980 population residing in the study area. The 1985 population for cities was determined by interpolating the Bureau of Census 1984 and 1986 city population estimates. The 1985 "County Other" population estimates were based on U.S. Bureau of Census 1985 total county population estimates adjusted where appropriate for study area portion. Population projections are based on U.S. Bureau of Census 1990 Census of Population count and the TWDB population projections ***Draft*** dated June 1991.

The population of the study area decreased one percent during the period 1980 to 1990. The population of the study area is projected to increase by six percent from 1990 to the year 2000, and by 11 percent from 1990 to 2010. The highest projected growth for a major city within the study area is Merkel in Taylor county with 53 percent from 1990 to 2010. The highest projected growth in a county occurs in Palo Pinto County with a 27 percent increase by 2010.

Water Use

In 1988, a total of 301,030 acre-feet of ground and surface water was used in the study area of which 136,632 acre-feet of ground water was pumped from all aquifers. The Seymour Aquifer supplied approximately 80 percent of the total ground water for all use categories. The Blaine produced approximately 5 percent, the Dockum 4 percent, and other formations in the Pennsylvanian and Permian 11 percent. The quantity of water produced by type of use within the study area in 1988 is shown below:

	1988 Ground Water (acre-feet)	1988 Surface Water (acre-feet)
Public Supply	7,028	59,447
Rural	7,534	11,397
Manufacturing	726	8,341
Power	0	14,799
Irrigation	110,077	41,908
Mining	8,515	8,556
Livestock	2,752	19,950
Total	**136,632**	**164,398**

Source: Texas Water Development Board, 1991a

Public supply and rural use are based on amounts reported by cities or other suppliers and apportioned by population where appropriate. Livestock use is based on the rural geographical share apportioned to county total livestock use. All other uses are based on site-specific computed use.

Public Supply

The municipal water needs of the various communities are supplied from ground-water sources and in some cases are supplemented by surface water. Total calculated amounts of ground and surface water pumped for public supply in 1988 of approximately 66,475 acre-feet account for 22 percent of the total water used in the study area. Table 2 lists the major communities within the entire study area and the quantity of water supplied to each in 1988.

Rural

The rural population of the study area is quite sparse, mostly concentrated around several unincorporated communities. In 1988, 7,534 acre-feet of ground water and 11,397 acre-feet of surface water were supplied for rural use. Ground water for rural domestic use is pumped from private wells or provided through community systems.

Manufacturing, Mining, and Power

Manufacturing, mining, and steam electric power generation represent the industrial use of water in the study area. In 1988, manufacturing use amounted to 726 acre-feet of ground water which was partially supplied from municipal sources. Ground water pumped for mining operations amounted to 8,515 acre-feet in 1988. Most of the pumpage was from the Pennsylvanian and Permian Formations with lesser amounts from the Dockum, Seymour, and Blaine aquifers. Pumpage for mining purposes is almost exclusively related to the petroleum industry, including such operations as water flooding for secondary recovery, operation of gasoline plants and compressor stations, and drilling of oil and gas wells. Ground water was not used in the generation of steam electric power, but 14,799 acre-feet of surface water was used in this operation.

Table 2.–Current and Projected Population in the Study Area[1], 1980–2010

	1980	198S	1990	2000	2010
Major Cities [2]	383,806	405,953	377,708	407,161	429,166
County Other [3]	103,544	107,160	105,710	104 ,142	107 ,928
Total	**487,350**	**513,113**	**483,418**	**511,303**	**537,094**
Archer	7,266	7,793	7,859	8,595	9,084
Armstrong [4]	152	150	141	135	121
Baylor	4,919	5,372	4,727	4,699	4,584
Bordon [4]	17	20	15	16	16
Briscoe [4]	919	863	659	749	805
Callahan [4]	3,478	3,824	3,646	3,912	4,179
Childress	6, 950	6, 506	5, 951	5, 916	5, 950
Clay	10, 446	10, 672	11, 012	11, 376	11, 786
Collingsworth	4,623	4,076	3,557	3,415	3,262
Cottle	2, 425	2, 165	1, 847	1, 839	1, 901
Crosby [4]	575	526	397	427	481
Dickens	3,291	2,890	2,408	2,270	2,259
Donley [4]	562	542	494	549	563
Eastland [4]	13, 814	14, 743	12, 894	12, 728	12, 682
Erath [4]	460	541	654	839	1,079
Fisher	4,928	4,282	3,669	3,790	3,874
Floyd [4]	123	114	89	100	100
Faard	2,092	1,770	1,728	1,660	1,583
Garza [4]	4,864	5,020	4,694	4,840	4,930
Hall	5, 594	4, 758	3, 905	3, 632	3, 377
Hardeman	6,368	6,430	5,283	5,054	4,861
Haskell	9, 082	8, 947	8, 539	8, 349	8, 029
Jack	7, 098	7, 384	6, 651	6, 897	7, 000
Kent	1,145	1,251	1,010	987	894
Jones	16,765	17,317	15,693	15,912	16,093
King	1, 013	973	820	861	883
Knox	5,329	5,640	4,837	4,716	4,697
Montague [4]	9,451	10,133	9,641	9,934	10,158
Motley	1,883	1,694	1,477	1,342	1,246
Nolan [4]	15, 963	16, 648	15, 616	16, 702	18, 263
Palo Pinto	24, 020	26, 235	25, 008	27, 705	31, 888
Parker [4]	2,274	2,782	3,779	4,499	4,994
Randall [4]	4	4	4	4	4
Scurry [4]	18, 192	19, 774	18, 634	20, 022	20, 840
Shackelford	3,915	3,986	3,316	3,313	3,246
Stephens	9,926	10,438	9,010	9,214	9,581
Swisher [4]	0	0	0	0	0
Stonewall	1, 049	792	294	295	291
Taylor [4]	109, 538	122, 856	117, 802	134, 263	147, 069
Throckmorton	2, 053	2, 291	1, 880	1, 742	1, 571
Wheeler [4]	3,893	3,789	3,143	2,979	2,861
Wichita	120,377	124,809	121,544	123,821	126,409
Wilbarger	15,772	16,823	14,967	14,850	14,737
Wise [4]	5,659	6,429	6,226	7,361	8,614
Young	19,083	19,061	17,898	18,994	20,249
Total	**487,350**	**513,113**	**483,418**	**511,303**	**537,094**

1 1980, 1985 and 1990 population is based on Bureau of Census Statistics. 2000 and 2010 population is based on TWDB *Draft* June1991 High Series population projection.

2 The term "Major Cities" includes incorporated cities with a 1980 population of 1,000 or greater, or a county seat with less than 1,000 population in 1980.

3 The term "County Other" includes cities and unincorporated areas with a 1980 population of less than 1,000 and all rural population.

4 Indicates a county where only that portion of the population that falls within the study area is included.

Table 3 —Major Cities and 1988 Water Use

City	Ground-Water (acre-feet)	Surface-Water (acre-feet)
Archer	0	357
Seymour	753	0
Baird	0	247
Childress	0	842
Henrietta	0	560
Wellington	551	0
Paducah	442	0
Dickens	83	0
Cisco	0	595
Eastland	0	1,224
Ranger	0	707
Roby	7	60
Rotan	0	267
Crowell	0	311
Post	0	786
Memphis	427	73
Chillicothe	116	0
Quanah	0	694
Aspermont	144	97
Haskell	0	491
Rule	73	50
Stamford	0	779
Jacksboro	0	360
Anson	0	461
Hamlin	0	673
Jayton	140	0
Guthrie	51	0
Benjamin	0	71
Knox City	0	257
Munday	0	282
Nacona	0	440
Matador	222	0
Roscoe	246	0
Sweetwater	312	2,826
Mineral Wells	0	2,814
Palo Pinto	0	60
Snyder	0	2,504
Albany	0	536
Brackenridge	0	1,277
Abilene	113	17,889
Merkel	3	442
Tye	1	153
Throckmorton	0	220
Shamrock	406	0
Burkburnett	747	777
Electra	334	212
Iowa Park	0	1,097
Wichita Falls	0	14,504
Vernon	2,227	0
Bridgeport	0	368
Graham	0	2,094
Olney	0	534

Source: Texas Water Development Board, 1991a

Irrigation

Irrigation represents the largest category of ground-water use in the study area. In 1988, approximately 110,077 acre-feet of ground water was pumped from all aquifers for irrigation. This represents about 81 percent of all ground water pumped in the study area. Approximately 95,613 acre-feet was pumped from the Seymour aquifer which represents approximately 86 percent of the ground water used for irrigation. The majority of the irrigation occurred in Wilbarger, Knox, and Haskell Counties. These three counties pumped about 51,522 acre-feet which represents approximately 47 percent of ground water used for irrigation (TWDB, 1991a).

Prior to 1943, the use of ground water for irrigation within Wilbarger County was minimal. Follett and others (1944) reported no more than 24 irrigation wells were in use prior to 1943, with most of the wells located in the west-central part of the county. Irrigation development began in Wilbarger County during the 1950s. The first irrigation supplies in Knox and Haskell Counties were developed in 1938 with over half of the irrigation wells being drilled during the drought of the 1950s. Harden (1978) reported the number of irrigation wells in Haskell and Knox Counties increased from approximately 115 in 1952 to 1,100 in 1956.

During the late 1960s when sprinkler irrigation of land unsuitable for row irrigation became popular a large number of wells were drilled. As of 1989, approximately 4,369 irrigation wells are reported to be in use in the study area (TWDB, 1991c).

The 1989 irrigation summary by county, irrigated acreage, and water quantity in the study area are shown in Table 4. Between 1958 and 1989, the amount of ground water pumped for irrigation in Haskell, Knox, and Wilbarger Counties increased from 54,544 to 81,906 acre-feet (TWDB, 1991c).

Livestock

The amount of ground water pumped from all aquifers within the study area for livestock purposes in 1988 was approximately 2,752 acre-feet. 19,950 acre-feet of surface water was the primary source for livestock use.

Projected Water Demand, 1990-2010

Under projected conditions, the total annual water requirement for the study area is expected to increase by approximately 30 percent from 1990 to year 2010, at which time the annual demand is estimated to be 390,327 acre-feet. Current and projected water demands for the study area are shown in Table 5.

Table 4. 1989 Irrigation Summary by Acreage and Water Source[1]

County	Ground Water Acres	Ground Water Supplied (ac/ft)	Surface Water Supplied (ac/ft)
Archer	200	——	333
Baylor	3,525	1,857	——
Childress	6,405	5,829	——
Clay	544	298	200
Collingsworth	10,999	12,917	17
Cottle	801	439	30
Fisher	1,840	2,149	328
Foard	4,100	4,101	——
Hall	14,863	11,763	——
Hardeman	7,147	6,090	82
Haskell	28,630	26,040	——
Jack	48	4	——
Jones	8,761	3,532	1,792
Kent	530	691	——
King	30	30	——
Knox	42,305	35,361	——
Palo Pinto	351	5	575
Scurry	785	621	188
Shackelford	397	259	——
Stephens	932	22	374
Stonewall	524	489	24
Wichita	12,523	——	31,018
Wilbarger	15,613	20,505	790
Young	611	306	162
TOTAL	**162,464**	**133,308**	**35,913**

[1] Data from Texas Water Development Board Report 329

Municipal and rural requirements are expected to increase water demands by 28 percent to 109,696 acre-feet by the year 2010. Although the increase from 1990 to 2010 in manufacturing is expected to be approximately 91 percent, a significant portion of this increase is due to less than full use of existing production capacity available during the 1980s which is expected to return to full production. New growth is expected to reach approximately 38 percent by 2010. Water use for power generation will increase by 33 percent. Mining use is expected to decrease by 35 percent, and livestock use will increase by 34 percent.

Projections of future public supply and rural water requirements are based on the Texas Water Development Board Draft of June 1991 projected high per capita water use with conservation series. High series projections take into account the demands that are likely to occur during periods of less than normal rainfall conditions. All other water use projections are based on the Texas Water Development Board high series projected demands, dated June 1991.

Table 5.–Historical and Projected Demands for Ground and Surface Water (Units in Acre-feet)

	1980	1985	1990 [1]	2000 [2]	2010 [2]
Municipal Use					
Major Cities [3]					
Ground	8,857	8,357	7,398		
Surface	74,575	60,864	59,447		
Sub-Total	83,432	69,221	66,845	87,837	88,839
County Other [4]					
Ground	8,696	7,805	7,573		
Surface	9,514	12,190	11,397		
Sub-Total	18,210	19,995	18,970	21,201	20,857
Municipal and County Other Use					
Total	**101,642**	**89,216**	**85,815**	**109,038**	**109,696**
Other Uses [5]					
Ground	214,797	133,936	122,070		
Surface	120,406	122,039	93,554		
Total	**335,203**	**255,975**	**215,624**	**281,178**	**280,631**
Study Area					
Ground	232,350	150,098	137,041		
Surface	204,495	195,093	164,398		
Total	**436,845**	**345,191**	**301,439**	**390,216**	**390,327**

[1] Recorded calendar year 1988 use apportioned by population

[2] Includes ground and surface water.

[3] The term "Major Cities" includes incorporated cities with a 1980 population of 1,000 or greater, or a county seat with less than 1,000 population in 1980.

[4] The term "County Other" includes cities and unincorporated areas with 1980 population of less than 1,000 and all rural population.

[5] Includes irrigation, manufacturing, power, mining, and livestock.

AVAILABILITY OF WATER

Current Availability of Ground Water

The 1980 estimates of recoverable volumes of fresh to slightly saline ground water in storage from all aquifers in the study area are approximately 428,000 acre-feet: volume in the Seymour is approximately 268,300 acre-feet; volume in the Blaine is 142,600 acre-feet ; volume in the Dockum is 14,700 acre-feet; and volume in the others is 2,400 acre-feet. The total estimated annual effective recharge to all aquifers is 366,900 acre-feet per year. Approximately 136,600 acre-feet of ground water was pumped from all aquifers in 1988 which is 2.5 times less than the amount of ground water replenished. Therefore, except in areas of heavy pumpage and during periods of excessive dryness, sufficient ground water should be available for most use through the year 2010.

Current Availability of Surface Water

Currently, 25 major surface reservoirs with capacities of 5,000 acre-feet or more as shown on Figure 15 contribute all or part of their respective yields to supply needs within the study area. These reservoirs have combined capacities of more than 2.2 million acre-feet. The combined supplies available from these 25 reservoirs total over 0.62 million acre-feet in the study area.

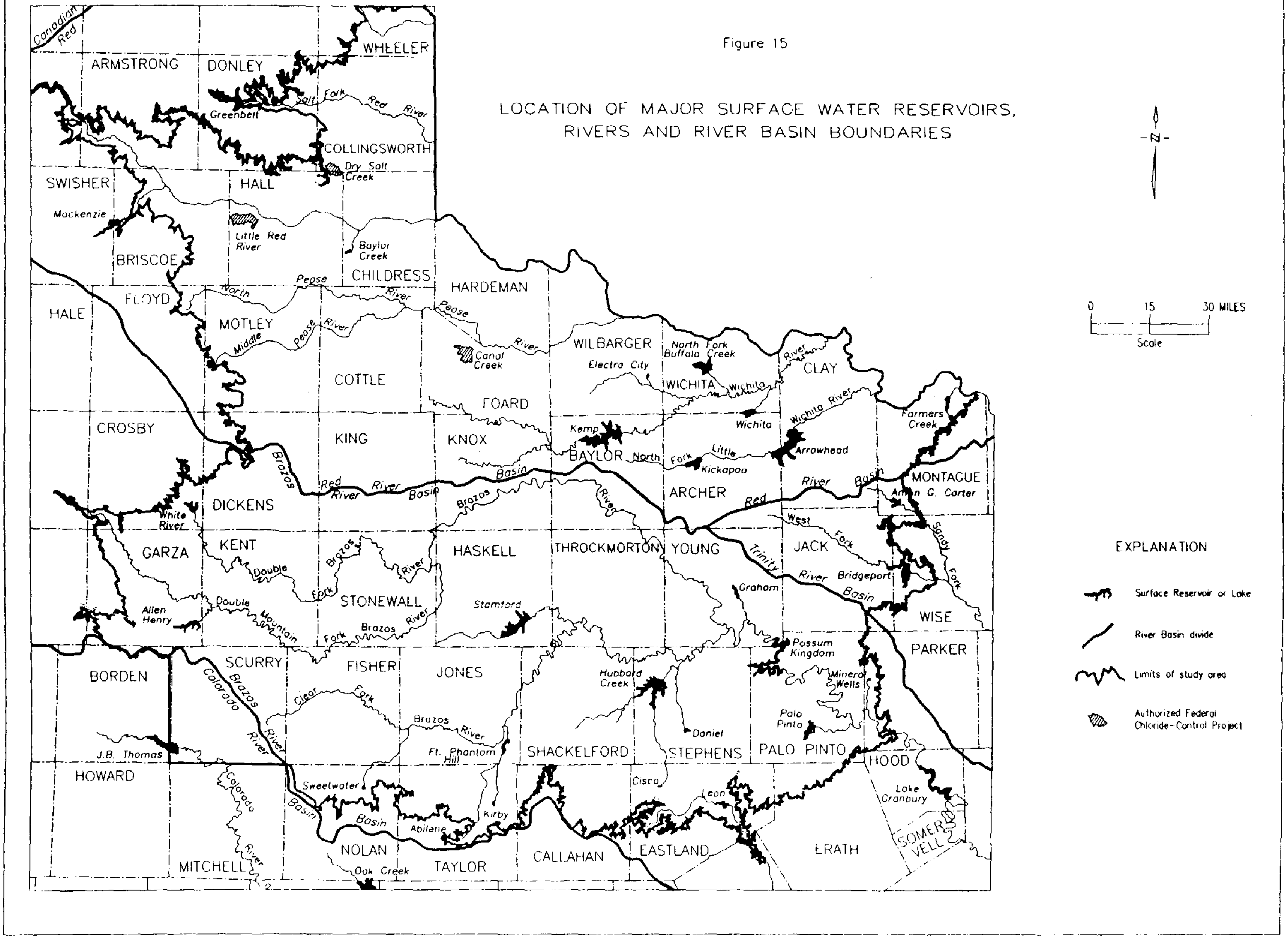
The MacKenzie reservoir in the Red River Basin, Bridgeport and Amon Carter reservoirs in the Trinity River Basin, and Allen Henry reservoir in the Brazos River Basin have portions of supplies allocated to users outside the study area. J.B. Thomas and Oak Creek reservoirs located outside the study area in the Colorado River Basin allocate a portion of their supplies to users inside the study area. The City of Abilene also has contracted for 16 percent of O.H. Ivie reservoir. Although not currently used, it is projected that the city could need these supplies by 2010.

In addition to major reservoirs, several smaller reservoirs with capacities less than 5,000 acre-feet exist within the area and supply local needs. Surface-water supplies are adequate to meet current and projected needs through the year 2010.

The natural salt contamination of the surface-water resources is a major problem in the upper reaches of the Red and Brazos River Basins and precludes full utilization of the water resources of these basins. These high concentrations are primarily of natural origin from salt water springs and outcrops of gypsum beds. The salt springs are located in the western portion of the study area—particularly in the upper reaches of the Wichita River, the North and South Forks of the Pease River, and tributaries to the Salt Fork of the Brazos River. Large quantities of calcium and sulphate are also contributed to the streams from the solution of gypsum beds which are wide spread throughout most of the study area. As a result of the natural salt pollution, waters in many of the streams draining the area are too saline for many uses.

Figure 15

LOCATION OF MAJOR SURFACE WATER RESERVOIRS, RIVERS AND RIVER BASIN BOUNDARIES



To improve water quality and expand future useable supplies, federal chloride control projects have been constructed. Such projects include Canal Creek, Little Red River, and Dry Salt Creek diversion lakes (TWDB, 1990b) (Figure 15).

Potential for Conjunctive Use of Ground and Surface Water

Conjunctive use ideally involves management of both ground- and surface-water resources in order to obtain maximum utilization of the total resources in the most economic and equitable manner. The term conjunctive use is, however, commonly used in reference to any type of arrangement where one source is used to supplement the other in time of need.

Conjunctive use in the study area is desirable, and undoubtedly substantial benefits are derived from such an arrangement because of the substandard water quality encountered. In areas where surface or ground-water quality is significantly poor and substandard for treatment, it may be possible to mix it with higher quality water. This would result in increasing the overall availability of usable water supplies and avoiding the need for development of new and costly supply sources. Conjunctive use programs can involve surface supplies as much as possible and ground-water supplies to meet peak demands when surface water is not available. Ground water does not evaporate as does water in a lake and is not as dependent on recent rainfall. Conjunctive use is currently practiced to a limited degree in the study area. Of the 52 major cities or towns, 31 used surface water, 11 used ground water, and 10 used both ground and surface water-sources to supply their water needs in 1988.

Potential Methods of Increasing Aquifer Recharge

Factors determining the amount of recharge to an aquifer include the amount and frequency of precipitation, areal extent of the outcrop, topography, type and amount of vegetation, condition of the soil in the outcrop, and permeability of the aquifer. Any activity by man, either intentional or unintentional, that increases or supplements the rate of replenishment to the aquifer, is called artificial recharge. Following are suggestions of methods to artificially enhance recharge in the study area:

Trapping rainwater runoff to provide a water supply in some areas provides additional time for recharge to occur. This requires damming some natural drainage channels and is already common practice throughout the area to provide "stock tanks". A few attempts have been made to drain water that collects in the shallow "tanks" during periods of heavy precipitation into wells. On a farm about 2 miles west of the community of O'Brien in Haskell County, a well was drilled to drain water from about 120 acres of land. The primary purpose of the recharging, however, was to reclaim land, not to conserve water. Experiments using wells for artificial recharge have been tried in several parts of the Southern High Plains of Texas, but many have proven unsatisfactory because the wells soon became clogged with silt.

Some farmers on the High Plains have installed dual-purpose wells for irrigating their farms and draining their ponds. A dual-purpose well is equipped to drain pounded water through the annular space between the pump column and the casing; the well also is equipped with a pump so that it can be surged, thus removing the silt deposited in the well and the formation near the well by the injected water. During periods when no recharge water is available, the well is used for irrigation.

Shallow depressions which naturally impound water during periods of heavy precipitation are common in north-central Haskell and south-central Knox Counties. They are less than 10 feet deep and generally cover an area of 10 to 150 acres. Some of the depressions appear to lose water rapidly, part of the water undoubtedly recharging the aquifer. If additional water could be diverted to these areas, recharge could be increased.

Projected Availability through the Year 2010

There are a number of stratigraphic units that supply fresh to moderately saline ground water in the study area which include formations of Pennsylvanian, Permian, Triassic, and Quaternary ages. The most important aquifers in the study area are the Seymour, Dockum, and Blaine. Ground- and surface-water supplies are adequate to meet current and projected needs through the year 2010.

The Seymour aquifer consists of isolated areas of alluvium which occur in parts of twenty-two north-central counties in the study area. These local aquifers are used primarily for irrigation. In some localized areas the salinity has increased to the point that the water has become unsuitable for domestic and municipal use. Ground water in these areas also contains a relatively high concentration of nitrate. It is estimated that current withdrawals from the Seymour total about one-half of the average annual recharge and that future water needs will remain at the current levels.

The Dockum Formation occurs in the southwestern part of the study area and is used mainly for domestic and livestock and for oil field water-flooding operations. Annual recharge greatly exceeds current pumpage. It is anticipated that pumpage will remain at current levels.

The Blaine aquifer, located in the northern portion of the study area, is used almost exclusively for irrigation. The quality of the water varies from slightly to moderately saline and yields vary from one location to another. Only 5 percent of the estimated annual effective recharge is currently being used.

The water-bearing Pennsylvanian and Permian rocks occur in local areas and are commonly the only source of ground water available. Aquifers in these groups provide small to moderate quantities of fresh to slightly saline water which are used mostly for domestic and livestock purposes. Currently, pumpage from these formations is relatively small and, due to the limited extent of productive formations, future pumpage is likely to remain small.

Due to the large amount of saline water that exists in the region, additional fresh water could feasibly be made available through the process of desalinization. A detailed description of desalinization technology can be found in Appendix B of this report.

CONCLUSIONS

The region has experienced a decline in population, however, increased manufacturing activity near larger metropolitan areas seems to have encouraged stabilization or even an increase in population. Generally, most of the aquifers have experienced a rise in water levels except near the cities of Vernon and Childress. The results of the water quality analyses indicate that the region has some ground water of poor quality, and that some of the problems associated with the poor water quality were probably caused by pollution from oil field activity. An adequate quantity of ground-water and surface-water supplies exists to meet current and projected needs through the year 2010; however, the continued deterioration of the chemical quality could limit the usefulness of some of this water.

SELECTED REFERENCES

Abilene Geological Society, 1955, Study of the lower Permian and upper Pennsylvanian rocks in the Brazos and Colorado River valleys of west central Texas, together with a preliminary report on the structural development of west central Texas: Abilene Geological Society Guidebook, 36p.

Baker, E.T., Jr., Long, A.T., Jr., Reeves, R.D., and Wood, L.A., 1963, Reconnaissance investigation of the ground-water resources of the Red River, Sulphur River, and Cypress Creek Basins, Texas: Texas Water Commission Bulletin 6306, 127 p.

Baker, R.C., Hughes, L.S., and Yost, I.D., 1964, Natural resources of salinity in the Brazos River, Texas, with particular reference to the Croton Creek and Salt Croton Creek Basins: U.S. Geological Survey Water-Supply Paper 1669.

Bassett, R.L., and Bentley, M.E., 1983, Deep brine aquifers in the Palo Duro Basin: regional flow and geochemical constraints: University of Texas, Bureau Economic Geology Report of Invoice No. 130, 59 p.

Bayha, D.C., 1964, Occurrence and quality of ground water in Stephens County, Texas: Texas Water Commission Bulletin 6412, 96 p.

____, 1967, Occurrence and quality of ground water in Montague County, Texas: Texas Water Development Board Report 58, 81p.

Beede, J.W., and Christner, D.D., 1926, The San Angelo Formation and the geology of Foard County: University of Texas Bulletin 2607, 57 p.

Broadhurst, W.L., and Follett, C.R., 1944, Ground-water resources in the vicinity of Nocona, Montague County, Texas: Texas Board of Water Engineers, M190, 17 p.

____, 1944a, Preliminary report of ground-water resources near Stamford in Jones and Haskell Counties, Texas: U.S. Geological Survey open-file report, 11 p.

Broadhurst, W.L., Sundstrom, R.W., and Weaver, D.E., 1951, Public water supplies in western Texas: U.S. Geological Survey Water- Supply Paper 1106, 168 p.

Brown, L.F., Jr., 1959, Problems of stratigraphic nomenclature and classification, upper Pennsylvania, north-central Texas: Discussion Amercian Association of Petroleum Geologists, v. 43, p. 2866-2871.

____, 1962, A stratigraphic datum, Cisco Group (upper Pennsylvanian), Brazos and Trinity valleys, north-central Texas: University of Texas, Bureau of Economic Geology Report of Inv. 46, 42 p.

Bullard, F.M., and Cuyler, R.H., 1930, A preliminary report on the geology of Montague County, Texas, in Contributions to geology, 1930: University of Texas Bulletin 3001, p. 57-76.

Burnitt, S.C., 1963, Reconnaissance of soil damage and ground- water quality, Fisher County, Texas: Texas Water Commission Memorandum Report 63-02, 49 p.

Bureau of Economic Geology, 1967, Geologic Atlas of Texas, Sherman sheet: University of Texas, Bureau of Economic Geology Map.

____, 1967a, Geologic atlas of Texas, Lubbock sheet: University of Texas, Bureau of Economic Geology Map.

____, 1968, Geologic atlas of Texas, Plainview sheet: University of Texas, Bureau of Economic Geology Map.

Bureau of Economic Geology, 1969, Geologic atlas of Texas, Amarillo sheet: University of Texas, Bureau of Economic Geology Map.

____, 1972, Geologic atlas of Texas, Abilene Sheet: University of Texas, Bureau of Economic Geology Map.

____, 1974, Geologic atlas of Texas, Big Spring sheet: University of Texas, Bureau of Economic Geology Map.

____, 1987, Geologic atlas of Texas, Wichita Falls-Lawton sheet: University of Texas, Bureau of Economic Geology Map.

Cheney, M.G., Geology of north-central Texas: Bulletin American Association of Petroleum Geologists, v. 24, no. 1, p. 65-118.

Cleaves, A.W., and Erxleben, A.W., 1982, Upper Strawn and Canyon (Pennsylvanian) depositional systems, surface and subsurface, north-central Texas: in Cromwell, D. (ed), Middle and Upper Pennsylvanian System of northcentral and west Texas (outcrop to subsurface) – Symposium and field conference guidebook: Permian Basin Section-S.E.P.M. Publication 82-21, p. 49-85.

Core Laboratories, Inc., 1972, A survey of the subsurface saline water of Texas: Texas Water Development Board Report 157, v. 1, 113 p.

Criswell, D.R., 1942, Geologic studies in Young County, Texas: University of Texas Mineral Resource Survey Circular 49, p. 5.

Cronin, J.G., 1972, Ground water in Dickens and Kent Counties, Texas: Texas Water Development Board Report 158, 80 p.

Cronin, J.G., Follett, C.R., Shafer, G.H., and Rettman, P.L.,1963, Reconnaissance investigation of the ground-water resources of the Brazos River Basin, Texas: Texas Water Commission Bulletin 6310, 153 p.

Dallas Morning News, 1987 Texas almanac and state industrial guide, 1988-1989: A.H. Belo Corp. 704 p.

Davis, S.N., and DeWiest, R.J.M., 1966, Hydrogeology: New York, John Wiley and Sons, Inc.

DeLeon, Fernando, Unpublished water-quality analysis program, Texas Railroad Commission.

DeWiest, R.J.M., 1965, Geohydrology: New York, John Wiley and Sons, Inc., p. 133-134.

Dowell, C.L., 1964, Dams and reservoirs in Texas, historical and descriptive information: Texas Water Commission Bulletin 6408, 256 p.

Drever, J.I., 1982, The geochemistry of natural waters: N.J. Prentice-Hall, Inc., 388 p.

Dutton, A.R., and Simpkins, W.W., 1986, Hydrogeochemistry and water resources of the Triassic Lower Dockum Group in the Texas Panhandle and Eastern New Mexico: University of Texas, Bureau of Economic Geology Report of Inv. No. 161, 51 p.

Dutton, S.P., Finley, R.J., Galloway, W.E., Gustavson, T.C., and Presley, M.W., 1979, Geology and geohydrology of the Palo Duro Basin, Texas Panhandle, A report on the progress of nuclear waste isolation feasibility studies (1978): University of Texas, Bureau of Economic Geology Geological Circular 79-1, p. 87-95.

Eargle, D.H., 1960, Stratigraphy of Pennsylvanian and lower Permian rocks in Brown and Coleman Counties, Texas: Geological Society Professional Paper 315-D, 77 p.

Eaton, F.M., 1950, Significance of carbonates in irrigation waters: Soil Science, v. 59, p. 123-133.

Erxleben, A.W., 1975, Depositional systems in Canyon Group (Pennsylvanian System), north-central Texas: University of Texas, Bureau of Economic Geology Report of Inv. 82, 76 p.

Fink, B.E., 1963, Ground-water geology of Triassic deposits, northern part of the Southern High Plains of Texas: High Plains Underground Water Conservation District, No. 1, Report 163, 76 p.

Follett, C.R., Sundstrom, R.W., and White, W.N., 1944, Ground-water resources in the vicinity of Vernon, Texas: Texas Board of Water Engineers, M286, 46 p.

Frye, J.C., and Leonard, A.B., 1963, Pleistocene geology of Red River Basin in Texas: University of Texas, Bureau of Economic Geology Report of Inv. 49, 48 p.

Galloway, W.E., and Brown, L.F., Jr., 1972, Depositional systems and shelf-slope relationships in Upper Pennsylvanian rocks, north-central Texas: University of Texas, Bureau of Econ. Geology Report of Inv. 75, 62 p.

Garrett, M.M., Lloyd, A.M., and Laskey, G.E., 1930, Geologic map of Baylor County, Texas: University of Texas, Bureau of Economic Geology county geologic map.

George, W.O., 1940, Callahan County, Texas - Records of wells and springs, drillers' logs, water analyses, and map showing locations of wells and springs: Texas Board of Water Engineers M029, 4 p.

____, 1945, Exploration for ground water at Childress, Texas: U.S. Geological Survey open-file report, 12 p.

George, W.O., and Foster, C.V., 1942, Childress County, Texas, record of wells, drillers logs, water analyses, and map showing locations of wells: Texas Board of Water Engineers, M050, 39p.

George, W.O., and Hastings, W.W., 1951, Nitrate in the ground water of Texas: American Geophys. Union Trans., v. 32, no. 3, p. 450-456.

Gordon, C.H., 1913, Geology and underground waters of the Wichita region, north-central Texas: U.S. Geological Survey Water - Supply Paper 317, 88 p.

Hall, William, Railroad Commission of Texas, personal communication, 1991.

Harden, R.W., 1978, The Seymour Aquifer, Ground-water quality and availability in Haskell and Knox Counties, Texas: Texas Department of Water Resources Report 226, v. 1, 63 p., v.2, 261 p.

Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water - Supply Paper 2254, 264 p.

Hendricks, Leo, 1957, Geology of Parker County, Texas: University of Texas, Publication 5724, 67 p.

Jackson, W.E., 1964, Depositional topography and cyclic deposition in west-central Texas: Bulletin American Association of Petr. Geologists, v. 48, pt. 1, p. 317-328.

Johnson, K.S., 1981, Dissolution of salt on the east flank of the Permian Basin in the southwestern U.S.A.: Journal of Hydrology, v. 54, p. 75-93.

Jones, D.C., 1973, An investigation of the nitrate problem in Runnels County, Texas: U.S. EPA-l; Office of Research and Monitoring; Washington, D.C.; Environmental Protection Technology Series EPA-R2-73-267, 215 p.

Jones, T.S., 1953, Stratigraphy of the Permian Basin of west Texas: West Texas Geological Society, p. 1-57.

Knowles, D.B., 1947, Ground water in northwestern Nolan County, Texas: Texas Board of Water Engineers, M196, 9 p.

Knowles, Tommy, Nordstrom, Phillip, and Klemt, W.B., 1984, Evaluating the ground-water resources of the High Plains of Texas: Texas Department of Water Resources Report 288, v. 1, 177 p.

Kreitler, C.W., 1975, Determining the source of nitrate in ground water by nitrogen isotope studies: University of Texas, Bureau of Economic Geology Report of Inv. No. 83, 57 p.

Kreitler, C.W., and Basset, R.L., 1983, Chemical and isotopic composition of saline ground water and saline springs in the Rolling Plains, east of the Ogallala Escarpment, in Gustavson, T.C., and others, Geology and geohydrology of the Palo Duro Basin, Texas Panhandle, a report on the progress of nuclear waste isolation feasibility studies (1982): University of Texas, Bureau of Economic Geology Geological Circular 83-4, p. 116-124.

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

Littleton, R.T., 1956, Contamination of surface and ground water in southeast Young County, Texas: Texas Board of Water Engineers, M305, 15 p.

McMillion, L.G., 1958, Ground-water geology in the vicinity of Dove and Croton Creeks, Stonewall, Kent, Dickens, and King Counties, Texas, with special reference to salt-water seepage: Texas Board of Water Engineers Bulletin 5801, 53 p., 11 figures, 2 plates

Maderak, M.L., 1972, Ground-water resources of Hardeman County, Texas: Texas Water Development Board Report 161, 45 p.

____, 1973, Ground-water resources of Wheeler and eastern Gray Counties, Texas: Texas Water Development Board Report 170, 66 p.

Mear, C.E., 1962, Stratigraphy of Permian outcrop, Coke County, Texas: Bulletin American Association Petr. Geologists v. 47, no.11, p. 1952-1962.

Moore, R.C., and others, 1944, Correlation of Pennsylvanian formations of North America: Geological Society of America Bulletin, v. 55, p. 657-706.

Morris, D.E., 1964, Occurrence and quality of ground water in Young County, Texas: Texas Water Commission Bulletin 6415, 106 p.

____, 1967, Occurrence and quality of ground water in Archer County, Texas: Texas Water Development Board Report 52, 83 p.

Mount, J.R., Rayner, F.A., Shamburger, V.M., Jr., Peckham, R.C., and Osborne, F.L., Jr., 1967, Reconnaissance investigation of the ground-water resources of the Colorado River Basin, Texas: Texas Water Development Board Report 51, 119 p.

Muller, D.A., and Price, R.D., 1979, Ground-water availability in Texas - Estimates and projections through 2030: Texas Department of Water Resources Report 238, 77 p.

Mylers, B.N., 1969, Compilation of results of aquifer tests in Texas: Texas Water Development Board Report 98, p. 6-7.

Nordstrom, P.L., 1988, Occurrence and Quality of Ground Water in Jack County, Texas: Texas Water Development Board Report 308, 97 p.

____, 1991, Joint ground-water quality project with the Texas Department of Agriculture in parts of Haskell, Knox, and Stonewall Counties, 1990: Texas Water Development Board Report 333, 85 p.

Nordstrom, P.L. and Beynon, B.E., Revised 1991, A field manual for ground water sampling: Texas Water Development Board UM-51, 57 p.

Ogilsbee, William, and Osborne, F.L., Jr., 1962, Ground-water resources of Haskell and Knox Counties, Texas: Texas Water Commission Bulletin 6209, 174 p.

Ohlen, Henry, 1956, Some Paleozoic sedimentary features in the subsurface of Jack, Palo Pinto, Parker, and Wise Counties, Texas, in Symposium of the Fort Worth Basin area and field study of the Hill Creek beds of the Fort Worth Basin area and field study of the Hill Creek beds of the Lower Strawn, southwestern Parker County, Texas: Society of Econ. Paleontologist and Mineralogists Permian Basin Section Spring Meeting and Field Symposium, May 11 and 12, 1956, p. 51-57.

Peckham, R.C., Souders, V.L., Dillard, J.W., and Baker, B.B., 1963, Reconnaissance investigation of the ground-water resources of the Trinity River Basin, Texas: Texas Water Commission Bulletin 6309.

Plummer, F.B., and Moore, R.C., 1921, Stratigraphy of the Pennsylvanian formations of north-central Texas: University of Texas Bulletin 2132, 237 p.

Popkin, B.P., 1973a, Ground-water resources of Donley County, Texas: Texas Water Development Board Report 164, 78 p.

____, 1973b, Ground-water resources of Hall and eastern Briscoe Counties, Texas: Texas Water Development Board Rept. 167, 84 p.

Preston, R.D., 1969, Occurrence and quality of ground water in Shackelford County, Texas: Texas Water Development Board Report 100, 58 p.

____, 1970, Occurrence and quality of ground water in Throckmorton County, Texas: Texas Water Development Board Report 113, 51 p.

____, 1977, Ground-water conditions in the vicinity of Jacksboro, Jack County, Texas: Texas Department of Water Resources LP4, 64 p.

____, 1978, Occurrence and quality of ground water in Baylor County, Texas: Texas Water Development Board Report 218, 117 p.

Price, R.D., 1978, The occurrence, quality, and availability of ground water in Jones County, Texas: Texas Department of Water Resources Report 215, 236 p.

____, 1979, Occurrence, quality and quantity of ground water in Wilbarger County, Texas: Texas Department of Water Resources Report 240, 231 p.

Price R.D., Walker, L.E., and Sieh, T.W., 1983, Occurrence, quality, and availability of ground water in Callahan County, Texas: Texas Department of Water Resources Report 278, 157 p.

Railroad Commission of Texas, and the Texas Petroleum Research Committee, 1968, A survey of secondary recovery and pressure maintenance operations in Texas to 1968: Bulletin 68, 470 p.

Rawson, Jack, Flugrath, M.W., and Hughes, L.S., 1968, Sources of saline water in the Upper Brazos River Basin, Texas: U.S. Geological Survey, Water Resources Division, Open-File Report no. 108.

Richter, B.C. and Kreitler C.W., 1986, Geochemistry of salt-spring and shallow subsurface brines in the Rolling Plains of Texas and Southwestern Oklahoma: University of Texas, Bureau of Economic Geology Report of Inv. No. 155, 47 p.

Richter, B.C., Dutton, A.R., and Kreitler, C.W., 1990, Indentification and sources of salt-water pollution affecting ground-water quality: A case study, West Texas: University of Texas, Bureau of Economic Geology Report of Inv. 191, 43p.

Russell, F.E., and Huggins, L.P., 1936, Hardeman County, Texas records of wells, drillers' logs, water analyses, and maps showing location of wells: Texas Board of Water Engineers, M107, 82 p.

Samuell, J.H., 1937, Stephens County, Texas, records of wells and drillers' logs: water analyses from wells, streams, and tanks; and map showing location of wells, streams, and tanks: Texas Board of Water Engineers, M270, 37 p.

Scofield, C.S., 1936, The salinity of irrigation water: Smithsonian Institute Annual Report, 1935, p. 275-287.

Scott, Gayle, and Armstrong, J.M., 1932, The geology of Wise County, Texas: University of Texas Bulletin 3224, 73 p.

Scott, G.L., and Ham, W.E., 1957, Geology and gypsum resources of the Croton area, Oklahoma: Oklahoma Geological Survey Circular 42, 64 p.

Sellards, E.H., Adkins, W.S., and Plummer, F.B., 1932, The geology of Texas, v. 1, Stratigraphy: University of Texas Bulletin 3232, 1007 p.

Shafer, G.H., 1957, The use of ground water for irrigation in Childress County, Texas: Texas Board of Water Engineers Bulletin 5706, 21 p.

Shamburger, V.M., Jr., 1960, A reconnaissance of alleged salt-contamination of soils near Stamford, Jones County, Texas: Texas Board of Water Engineers Contamination Report 6, 8 p.

____, 1967, Ground-water resources of Mitchell and western Nolan Counties, Texas: Texas Water Development Board Report 50,184 p.

Smith, J.T., 1970, Ground-water resources of Collingsworth County, Texas: Texas Water Development Board Report 119, 115 p.

____, 1973, Ground-water resources of Motley and northeastern Floyd Counties, Texas: Texas Water Development Board Report 165, 69 p.

Stafford, P.T., 1960, Stratigraphy of the Wichita Group in part of the Brazos River valley, north Texas: U.S. Geological Survey Bulletin 1081-G, p. 261-280.

Stafford, P.T. 1960a, Geology of the Cross Plains quadrangle, Brown, Callahan, Coleman, and Eastland Counties, Texas: U.S. Geological Survey Bulletin 1096-B, 72 p.

Stearman, J.W., 1960, A reconnaissance investigation of alleged contamination of irrigation wells near Lockett, Wilbarger County, Texas: Texas Board of Water Engineers, Contamination Report 8, 3 p.

Stramel, G.J., 1951, Ground-water resources of Parker County, Texas: Texas Board Water Engineers Bulletin 5103, 58 p.

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

Taylor, H.D., 1978, The occurrence and quality of ground water in Taylor County, Texas: Texas Department of Water Resources Report 224, 135 p.

Texas Department of Water Resources, 1984, Water for Texas-A comprehensive plan for the future, Texas Department of Water Resources GP-4-1, v. 1, 72 p., v. 2, Technical Appendix.

Texas Department of Health, 1977, Drinking water standards governing drinking water quality and reporting requirements for public water supply systems, revised November, 1988: Division of Water Hygiene, Texas Department of Health, dupl. report.

Texas Water Commission, 1962, Scope of salt water problem: Unpublished report, 13p.

____, 1988, The State of Texas Water Quality Inventory; 9th edition : Texas Water Commission LP 88-04, 606p.

____, 1989, Ground water quality of Texas - An overview of natural and man-affected conditions: Texas Water Commission Report 89-01, 197 p.

Texas Water Commission, and Texas Water Pollution Control Board, 1963, A statistical analysis of data on oil-field brine production and disposal in Texas for the year 1961 from an inventory conducted by the Texas Railroad Commission: Railroad Commission Dist. 6, v. 1, 327 p.

Texas Water Development Board, 1988, Ground-water conditions in Texas, 1980-1985: Texas Water Development Board Report 309, 53 p.

____, 1990a, Major and Minor aquifers of Texas: Texas Water Development Board.

____, 1990b, Water for Texas, today and tomorrow: Texas Water Development Board, Planning Document No.GP-5-1, 173 p.

____, 1991a, Draft data series, dated June 1991: Texas Water Development Board, unpublished data.

____, 1991b, Desalting in Texas, September, 1991: Unpublished Texas Water Development Board Report developed for inclusion in the Texas Water Plan update of 1992.

____, 1991c, Surveys of irrigation in Texas 1958, 1964, 1969, 1974, 1979, 1984, and 1989: Texas Water Development Board Report 329, 125 p.

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

Van Siclen, D.C., 1957, Cenozoic strata of the southwestern Osage Plains of Texas: Journal Geology, v. 65, no. 1, p. 47-60.

Walker, L.E., 1967, Occurrence and quality of ground water in Coleman County, Texas: Texas Water Development Board Report 57, 110 p.

Ward, P.E., 1961, Geology and ground-water features of salt springs, seeps, and plains in the Arkansas and Red River basins of western Oklahoma and adjacent parts of Kansas and Texas: U.S. Geological Survey Open - File Report 63-132, 94 p.

Wilcox, L.V., 1955, Classification and use of irrigation waters: U.S. Department of Agriculture Circular 969, 19 p.

Willis, G.W., and Knowles, D.B., 1953, Ground-water resources of the Odell Sand Hills, Wilbarger County, Texas: Texas Board of Water Engineers Bulletin 5301, 54 p.

Winslow, A.G., Doyel, W.W., and Gaum, C.H., 1954, Ground-water resources of Jones County, Texas: Texas Board of Water Engineers Bulletin 5418, 29 p.

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

Wood, W.W., 1976, Guidelines for collection and field analysis of ground-water samples for selected unstable constituents: U.S. Geological Survey Techniques of Water-Resources Inv. book 1, Chapter 12, 24p.

Appendix A
Ground-Water Quality Monitoring Evaluation

APPENDIX A

Ground-Water Quality Monitoring Evaluation

One of the most important tasks in water-quality sampling is to collect water which is representative of the aquifer. To insure that the water is from the aquifer itself, the well must first be purged, which means removing a sufficient volume of ground water stored in the well casing. The temperature, specific conductance, and pH are monitored until stabilization of the readings occurs. At that point, the well may be sampled. The sample should be collected near the wellhead before the water has gone through pressure tanks, water softeners, or other treatment. Standby, new, or little-used wells may require a day or more of pumping before the water is of constant quality (Wood, 1976).

Standardized procedures were used in collecting the ground-water samples for this investigation according to the Texas Water Development Board Field Manual for Ground Water Sampling (Nordstrom and Beynon, 1991). Analytical methods and detection limits are listed in Table 6.

Field sampling and laboratory analyses were completed during the first and second quarters of 1991. A total of 178 wells from 26 counties were sampled, representing nine geologic groups. Summaries of the field parameters and dissolved constituents of each group are given in their appropriate section. Overall, the ground water from these nine geologic groups is fresh to slightly saline and very hard.

The quality of the ground water within the study area is often not adequate for most domestic and irrigation uses. Most cities and counties in the region obtain their municipal supplies from surface water, although 11 cities obtain their water supplies from ground water: Seymour, Wellington, Paducah, Dickens, Chillicothe, Jayton, Guthrie, Matador, Roscoe, Shamrock, and Vernon. Many of the residents have connected to county water systems and only use their water wells for supplemental needs and watering livestock. This was particularly true for many landowners in the eastern half of the study area. Since the TWDB sampled wells which were still in use, many of the poorest quality wells no longer in use may have been missed. Therefore, the results of this study may not adequately reflect the worst-case conditions in these aquifers.

The Texas Department of Health has set the primary and secondary Maximum Concentration Levels (MCLs) for water which is used for human consumption. The standards for selected inorganic constituents can be found in Table 7.

Table 6.– Detection Limits and Analytical Methods for Selected Inorganic Species and Radioactive Elements.

	Symbol	Detection Limit	Method [1]
Dissolved Anions			
Bromide	Br	0.1 mg/l	Method 405
Chloride	Cl	1 mg/l	EPA Method 325.2
Fluoride	F	0.1 mg/l	EPA Method 325.2
Sulfate	S04	2 mg/l	EPA Method 375.2
Dissolved Cations/Metals			
Barium	Ba	10 μg/l	ICP [2]
Cadmium	Cd	10 μg/l	FAAS [3]
Calcium	Ca	1 mg/l	ICP
Iron	Fe	20 μg/l	ICP
Magnesium	Mg	1 mg/l	ICP
Potassium	K	1 mg/l	ICP
Sodium	Na	1 mg/l	ICP
Strontium	Sr	200 μg/l	ICP
Nutrients			
Nitrate	N03 (N)	0.01 mg/l	EPA Method 353.2
Radioactivity			
Gross Alpha	α	2.0 pCi/l	EPA Method 900.0
Gross Beta	β	4.0 pCi/l	EPA Method 900.0

[1] Unless otherwise specified, "Method" refers to *Standard Methods for the Examination of Water and Wastewater* (ACPHA, 1985).

[2] ICP- Induction Coupled Plasma, EPA Method 200.7

[3] FAAS- Flame AA, EPA Methods 213.1 (Cd), 239.1 (Pb), 272.1 (Ag)

Table 7.– Drinking Water Standards for Selected Inorganic Constituents and Radioactive Elements as Set by the Texas Department of Health.

Primary Constituents		
Arsenic	As	0.05 mg/l
Barium	Ba	1.0 mg/l
Cadmium	Cd	0.01 mg/l
Chromium	Cr	0.05 mg/l
Fluoride	F	4.0 mg/l
Lead	Pb	0.05 mg/l
Mercury	Hg	0.002 mg/l
Nitrate	NO_3	10 mg/l (as N)
Selenium	Se	0.01 mg/l
Silver	Ag	0.05 mg/l
Gross Alpha	α	15 pCi/l
Gross Beta	β	50 pCi/l
Radium	$Ra^{226} + Ra^{228}$	5 pCi/l
Secondary Constituents		
Chloride	Cl	300 mg/l
Copper	Cu	1.0 mg/l
Fluoride	F	2.0 mg/l (comm.)
Iron	Fe	0.30 mg/l
Manganese	Mn	0.05 mg/l
pH	pH	>7.0
Sulfate	$S0_4$	300 mg/l
Dissolved Solids	TDS	1000 mg/l
Zinc	Zn	5.0 mg/l

Modelling can be a useful tool in evaluating data because of the speed and efficiency of modern computers. One program developed by the Railroad Commission (De Leon, unpublished) was designed to find wells which show possible brine contamination by examining five parameters: (1) chloride/sulfate ratio; (2) chloride/sodium ratio; (3) Star diagram; (4) trilinear diagram; and (5) chloride content for all water analyses in a database. It then assigns one of five classifications to each parameter: Very Unlikely, Possible and Unlikely, Inconclusive, Possible and Likely, and Almost Certain. If any three parameters are either Possible and Likely or Almost Certain, the analysis is marked as a possible contaminated well.

This program was run on all water analyses in the TWDB database in 34 aquifer combinations in all of the counties included in the study area. Several requirements regarding water chemistry were established, and only those wells which met all of the criteria were analyzed by the program:

(1) Chloride concentration greater than 300 mg/l, which is the Maximum Contaminant Level (MCL) for chloride.

(2) Dissolved solids concentration greater than 1000 mg/l, which is the MCL for dissolved solids.

(3) Nitrate concentration less than 5 mg/l (as NO_3). Elevated nitrate concentrations may indicate salinization of shallow ground water by evaporative concentration at shallow water tables; subsurface brines normally do not contain appreciable amounts of nitrate (Richter and others, 1990).

(4) Charge-balance of the constituents must be ±5%.

In a study of salt-water resources in north-central Texas, Richter and Kreitler (1986) showed that the ionic ratios Na/Cl, Br/Cl, I/Cl, Mg/Cl, K/Cl, and $(Ca+Mg)/SO_4$ can be used to distinguish between salt water derived from dissolution of halite by shallow meteoric ground water and deep-basin brine moving long distances from the Midland Basin. Differentiation between salt-water sources is clearest when dissolved solids concentrations are greater than 10,000 mg/l. Whether these ionic ratios can be used to distinguish between salt-water sources where dissolved solids is less than 5,000 mg/l has not been determined (Richter and Kreitler, 1986).

Aquifer Nomenclature

Many individual aquifers are located within the boundaries of this study area because of the great number of discontinuous geological formations. The aquifer codes utilized in the TWDB database are adapted from the WATSTORE data file of the U.S. Geological Survey. The code consists of three digits designating the geological era, system, and series followed by a four- or five-digit alphabetical code designating the aquifer(s) or stratigraphic unit(s). A listing of the aquifer codes within each geologic group and the counties in which they are found is in Table 8.

Table 8. –Aquifers Sampled within Each County with Aquifer Codes.

Geologic Unit	Counties	Aquifer Codes
Alluvium	Stephens, Shackelford, King, Kent, Hardeman, Dickens, Wichita, Wilbarger, Throckmorton, Taylor	100ALVM 110ALVM 110AVTS 111ABZR
Seymour Formation	Wichita, Baylor, Foard, Wilbarger, Jones, Taylor, Knox, Stonewall, Haskell	112SYMR
Dockum Group	Motley, Fisher, Nolan, Dickens, Crosby, Garza, Kent, Scurry, Borden	231DCKM
Pease River Group	Collingsworth, Cottle, Dickens, Hardeman, Taylor, Wilbarger, Callahan, Fisher, Nolan, Wheeler, Motley, Eastland, Childress, Kent, King, Harris	313BLIN 310QRMW 318SAGL 310PRMN 313DCKB 313ARTS 313WTRS
Wichita-Albany Group	Archer, Clay, Montague, Shackelford	318WCHT 318PTRL 318LDRS
Clear Fork Group	Jones, Taylor	318CLFK 318CHOZ 318VALE
Cisco Group	Stephens, Shackelford, Jack, Eastland, Clay, Archer, Young, Wise	321GRHM 321TRFT 321TFGM 319MORN 321CSCO 319ARCT 321HPVL 319PUBL
Canyon Group	Stephens, Jack, Palo Pinto, Parker, Wise	321CLCK 321HMCK 321PLPT 321MARK 321PLPN
Strawn Group	Palo Pinto	324MLWL 324MWBR

Alluvium and Seymour

A total of 20 wells in ten counties representing four alluvial aquifers were sampled in 1991; and 68 wells in nine counties were sampled in the Seymour aquifer in 1990-91. Of the Seymour wells, 45 were sampled as part of a joint study with the Texas Department of Agriculture (TDA). Locations of all sampled wells, except for the joint TDA wells, and trilinear diagrams for the Alluvium and Seymour ground water are shown in Figure 16. A summary of the field parameters and dissolved constituents is found in Table 9 for the Alluvium and Table 10 for the Seymour.

After running the RRC program and examining the ionic ratios of the ground-water analyses, 14 alluvium wells show evidence of possible deep brine contamination (Table 11). Figure 17 shows the locations of each and their relationship to known oil and gas fields and known vegetation kill areas.

Because these wells produce water from alluvial aquifers, they are in close hydrologic contact with the surface water and mirror the chemical constituents of the river or stream. Many tributaries to the Red and Brazos Rivers have high dissolved constituents resembling deep brines because they receive water from the natural salt-spring discharges or they were polluted from oil-field activities prior to 1969. Particularly in Wilbarger County, many of the wells are near old vegetative kill areas and salt springs.

In the Seymour Formation, 30 wells were noted in the computer program as being possible brine contaminated wells (Table 12). These were found in Baylor, Jones, Knox, and Wilbarger Counties. Of these wells, 19 wells were in Jones County, and 8 were in Wilbarger County. Because of the high density of Seymour wells within a limited geographic area in these counties, the Seymour wells were not included in Figure 16. Like the Alluvium wells, the Seymour wells reflect nearby surface water quality.

Eighteen wells in the Alluvium aquifers exceeded drinking water standards in one or more constituents: 15 wells exceeded the standard for dissolved solids; 14 wells exceeded the standard for chloride; 13 wells exceeded the standard for sulfate; five wells exceeded the standard for nitrate; five wells exceeded the standard for iron; one well exceeded the standard for fluoride; and one well exceeded the standard for alpha radiation.

Sixty-one wells in the Seymour exceeded drinking water standards in one or more constituents: 51 wells exceeded the standard for nitrate; 25 wells exceeded the standard for dissolved solids; 16 wells exceeded the standard for chloride; 9 wells exceeded the standard for sulfate; three wells exceeded the standard for fluoride; and two wells exceeded the standard for alpha radiation.

Dockum Formation

A total of 47 wells in eight counties were sampled in the Dockum aquifer. The map showing the locations and a trilinear diagram for the wells sampled in 1989-91 are shown in Figure 18. A summary of the field parameters and dissolved constituents is found in Table 13.

Table 9. –Field Parameters and Dissolved Constituents of the Alluvium

Parameter/ Constituent	Concentration Range	Average Concentration
Temperature	17°C - 23°C	20°C
Specific Cond.	510 - 7,840 μmhos	2,803 μmhos
pH	6.5 - 8.0	6.9
Eh	-129.9 - +204.6 mV	+75.5 mV
Carbonate	0 mg/l	0 mg/l
Bicarbonate	205 - 615 mg/l	379 mg/l
Barium	<20 - 116 μg/l	52 μg/l
Bromide	0.22 - 9.87 mg/l	1.98 mg/l
Cadmium	Below Detect. Lim.	Below Detect. Lim.
Calcium	49 - 655 mg/l	251 mg/l
Chloride	12 - 2,352 mg/l	648 mg/l
Dissolved Solids	336 - 5,440 mg/l	2,229 mg/l
Fluoride	0.1 - 2.3 mg/l	0.7 mg/l
Hardness (as $CaCO_3$)	172 - 2,247 mg/l	998 mg/l
Iron	<20 - 3,620 μg/l	426 μg/l
Magnesium	11 - 204 mg/l	90 mg/l
Potassium	2 - 15 mg/l	6 mg/l
Sodium	19 - 1,290 mg/l	409 mg/l
Strontium	430 - 11,800 μg/l	2,943 μg/l
Sulfate	25 - 1,976 mg/l	612 mg/l
Nitrate (as NO_3)	<0.04 - 116.9 mg/l	30.0 mg/l
Alpha	<2 - 26 pCi/l	3.8 pCi/l
Beta	<4 - 6 pCi/l	<4 pCi/l

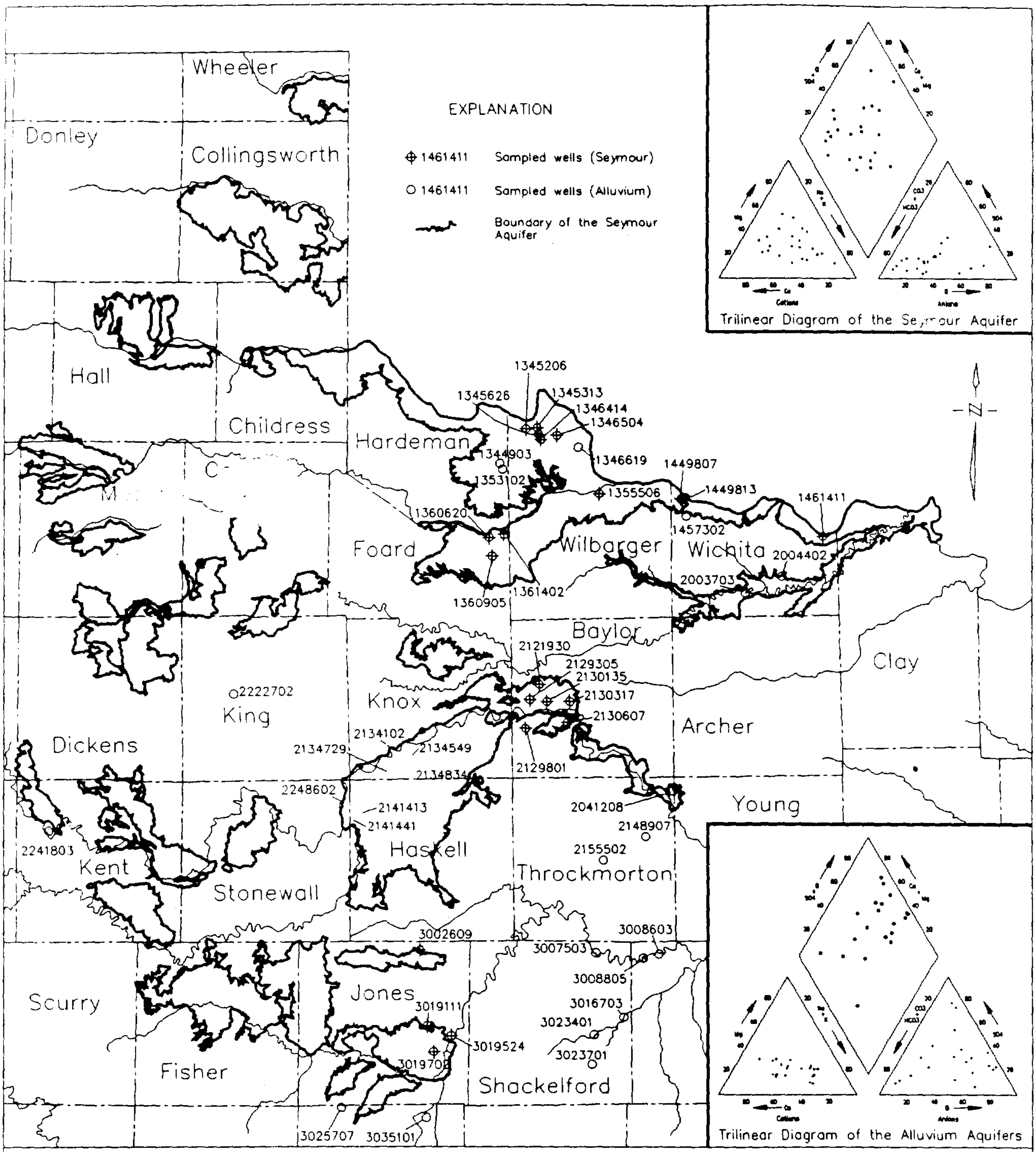


Figure 16

LOCATION AND TRILINEAR DIAGRAMS OF WELLS SAMPLED IN 1991 OF SEYMOUR AND ALLUVIUM AQUIFERS

Table 10.–Field Parameters and Dissolved Constituents of the Seymour.

Parameter/ Constituent	Concentration Range	Average Concentration
Temperature	17°C - 20°C	20°C
Specific Cond.	503 - 10,870 µmhos	1,707 µmhos
pH	6.7 - 7.4	7.2
Eh	75.6 - 335 . 2 mV	138.2 mV
Carbonate	0 mg/l	0 mg/l
Bicarbonate	227 - 599 mg/ 1	396 mg/1
Barium	<20 - 460 µg/l	127 µg/l
Bromide	0 . 46 - 11.10 mg/l	1. 57 mg/l
Cadmium	Below Detect. Lim.	Below Detect. Lim.
Calcium	37 - 420 mg/l	100 mg/l
Chloride	12- 2,490 mg/l	255 mg/l
Dissolved Solids	293 - 7,939 mg/l	1,111 mg/l
Fluoride	0.2 - 2.9 mg/l	1. 2 mg/l
Hardness (as $CaCO_3$)	190 - 3,594 mg/l	546 mg/l
Iron	<20 - 95 µmg/l	<20 µg/l
Magnesium	14 - 619 mg/l	72 mg/l
Potassium	1 - 19 mg/l	4 mg/l
Sodium	23 - 1,290 mg/l	188 mg/l
Strontium	320 - 15,600 µg/l	1,740 µg/l
Sulfate	18 - 1,405 mg/l	161 mg/l
Nitrate (as NO_3)	6 . 4 - 1,483 . 7 mg/l	137.3 mg/l
Alpha	<2 - 65 pCi/l	11.2 pCi/l
Beta	<4 - 23 pCi/l	9.9 pCi/l

Table 11. – **Alluvium Wells Which Show Evidence of Deep Brine Contamination**

Well Number	County
1347105	Wilbarger
1347406	Wilbarger
1354512	Wilbarger
1361204	Wilbarger
1361337	Wilbarger
1362527	Wilbarger
1457401	Wilbarger
1457402	Wilbarger
1457301	Wichita
1918705	Montague
2003503	Wichita
2140803	Throckmorton
3022603	Shackelford
3028803	Callahan

Table 12.– Seymour Wells which Show Evidence of Deep Brine Contamination.

Well Number	County
2129802	Baylor
2131803	Baylor
2932309	Jones
3002607	Jones
3002609	Jones
3002907	Jones
3003603	Jones
3010102	Jones
3017407	Jones
3019102	Jones
3019104	Jones
3019403	Jones
3019409	Jones
3015518	Jones
3019519	Jones
3019706	Jones
3019710	Jones
3019803	Jones
3019813	Jones
3026404	Jones
3027115	Jones
2135334	Knox
1345304	Wilbarger
1346118	Wilbarger
1346128	Wilbarger
1346427	Wilbarger
1355404	Wilbarger
1356501	Wilbarger
1361104	Wilbarger
1361701	Wilbarger

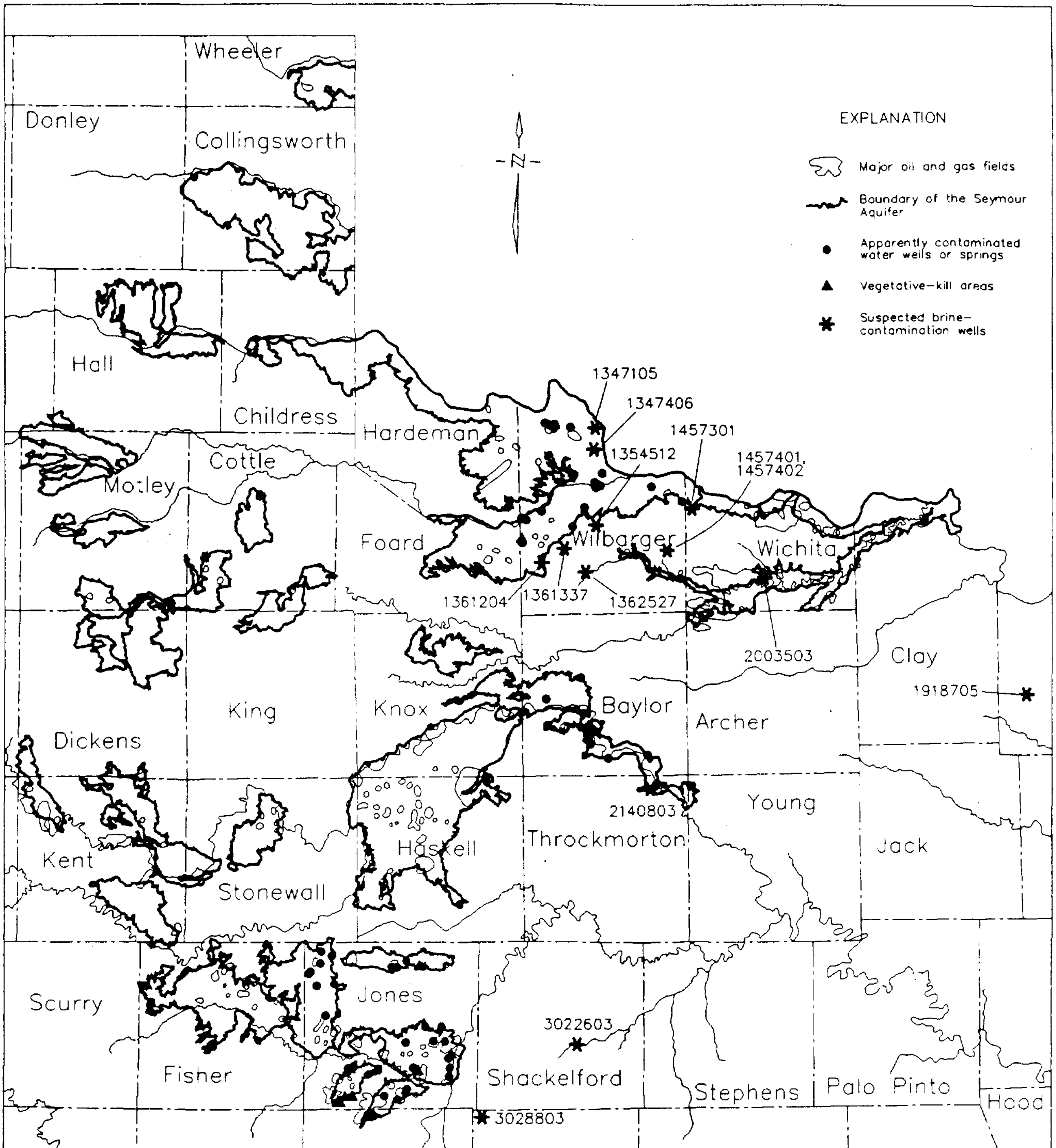


Figure 17

LOCATION OF ALLUVIUM WELLS WHICH SHOW
EVIDENCE OF DEEP BRINE CONTAMINATION

Table 13.--Field Parameters and Dissolved Constituents of the Dockum Formation

Parameter Constituent	**Concentration Range**	**Average Concentration**
Temperature	20°C - 21°C	20°C
Specific Cond.	588 - 2,110 µmhos	1,068 µmhos
pH	6.7 - 7.1	7
Carbonate	0 mg/l	0 mg/l
Bicarbonate	204 - 364 mg/1	283 mg/1
Barium	54 - 141 µg/1	86 µg/1
Bromide	0. 24 - 1.70 mg/l	0. 68 mg/l
Cadmium	Below Detect. Lim.	Below Detect. Lim.
Calcium	76 - 209 mg/l	108 mg/l
Chloride	29 - 416 mg/l	120 mg/l
Dissolved Solids	322 - 322 mg/l	662 mg/l
Fluoride	1.1 - 3.5 mg/l	2 mg/l
Hardness (as $CaCO_3$)	259 - 982 mg/l	453 mg/l
Iron	<20 - 83 µg/l	<20 µg/l
Magnesium	17 - 112 mg/l	45 mg/l
Potassium	4 - 12 mg/l	6 mg/l
Sodium	16 - 120 mg/l	58 mg/l
Strontium	7,110 - 14,900 µg/l	4,320 µg/l
Sulfate	34 - 319 mg/l	139 mg/l
Nitrate (as NO_3)	1. 5 - 123 . 2 mg/l	45.6mg/l
Alpha	<2 - 244 pCi/l	22.1 pCi/l
Beta	<4 - 193pCi/l	23.3 pCi/l

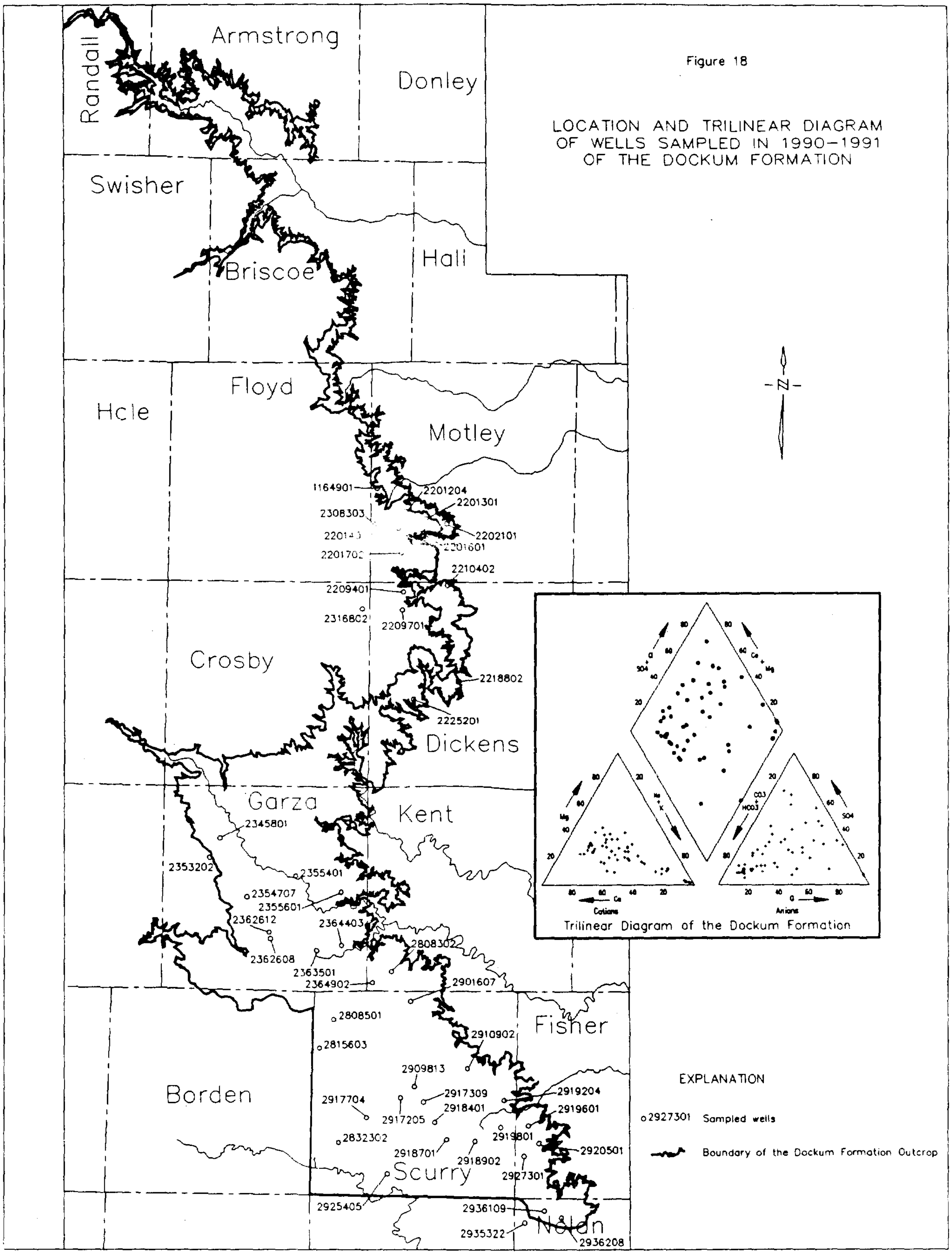


Figure 18

LOCATION AND TRILINEAR DIAGRAM OF WELLS SAMPLED IN 1990–1991 OF THE DOCKUM FORMATION

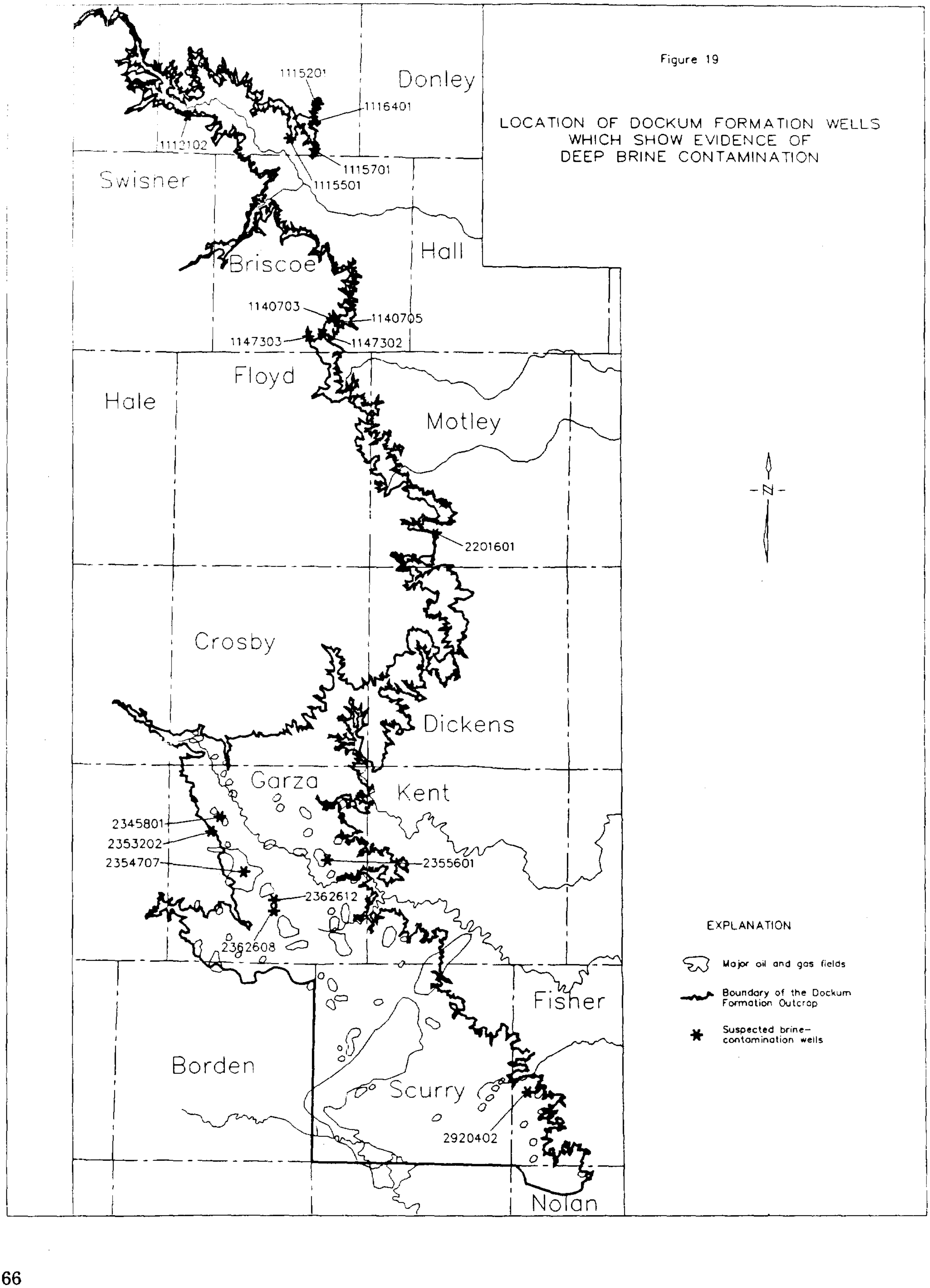


Figure 19

LOCATION OF DOCKUM FORMATION WELLS WHICH SHOW EVIDENCE OF DEEP BRINE CONTAMINATION

After running the RRC program and examining the ionic ratios of the water-quality analyses, 17 wells show evidence of deep brine contamination (Table 14). Figure 19 shows the locations of each and their proximity to known oil and gas fields and known vegetation kill areas.

Table 14.– Dockum Wells which Show Evidence of Deep Brine Contamination.

Well Number	County
11-12-102	Armstrong
11-15-201	Armstrong
11-15-501	Armstrong
11-15-701	Armstrong
11-16-401	Armstrong
11-40-703	Briscoe
11-40-705	Briscoe
11-47-302	Briscoe
11-47-303	Briscoe
22-01-601	Motley
23-45-801	Garza
23-53-202	Garza
23-54-707	Garza
23-55-601	Garza
23-62-608	Garza
23-62-612	Garza
29-20-402	Fisher

The locations of the Dockum wells which show evidence of deep brine contamination are near known oil and gas producing areas in the southern portion of the study area. However, the Dockum has gypsum within it which can cause poor water quality similar to a deep brine. The poor water quality noted in these wells is probably due to naturally occurring poor-quality water from the Dockum and does not reflect pollution due to the activities of man.

Twenty-seven wells in the Dockum exceeded drinking water standards in one or more constituents: 16 wells exceeded the standard for dissolved solids; 12 wells exceeded the standard for sulfate; 10 wells exceeded the standard for chloride; 10 wells exceeded the standard for fluoride; and six wells exceeded the standard for nitrate.

Pease River Group

A total of 43 wells in sixteen counties were sampled in seven aquifers within the Pease River Group. The map showing the locations and a trilinear diagram for the wells sampled in 1991 are shown in Figure 20. A summary of the field parameters and dissolved constituents is found in Table 15.

After running the RRC program and examining the ionic ratios of the water-quality analyses, 5 wells show evidence of deep brine contamination (Table 16). Figure 21 shows the locations of each and their proximity to known oil and gas fields and known vegetation kill areas. Like the Dockum, the Pease River has gypsiferous rocks which are water-bearing, such as the Blaine aquifer. These cause poor-quality water which can chemically resembles deep brines.

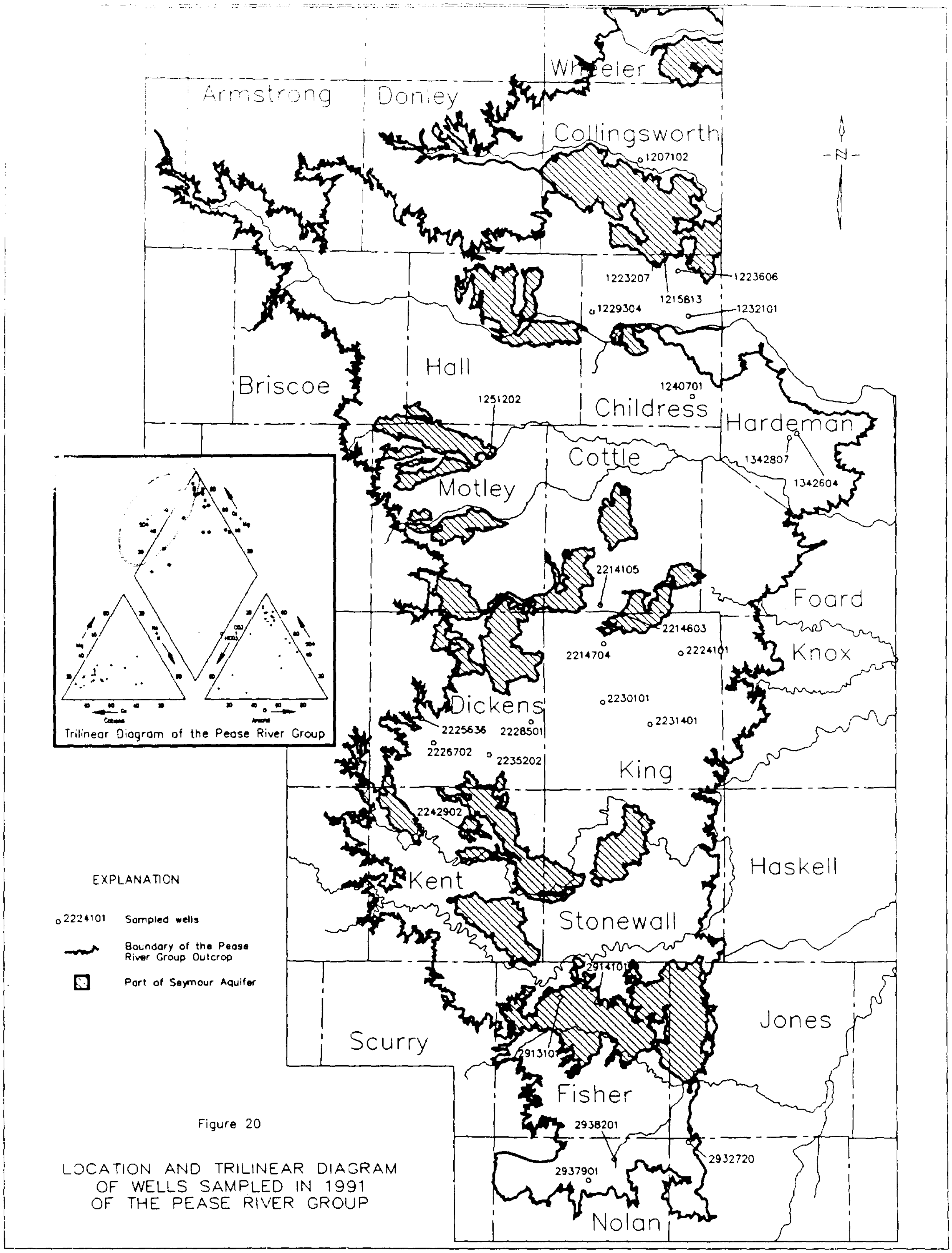


Figure 20

LOCATION AND TRILINEAR DIAGRAM OF WELLS SAMPLED IN 1991 OF THE PEASE RIVER GROUP

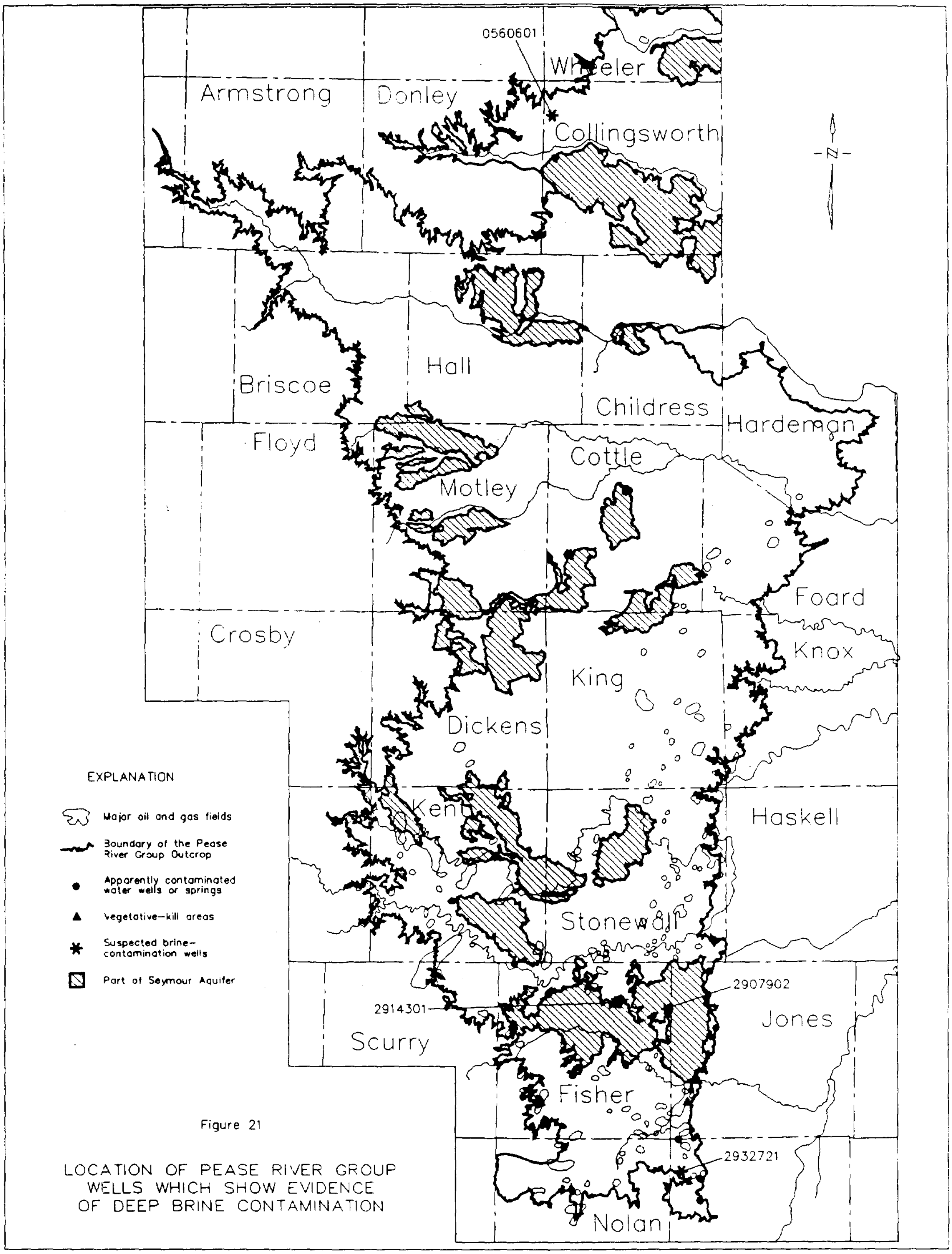


Figure 21

LOCATION OF PEASE RIVER GROUP WELLS WHICH SHOW EVIDENCE OF DEEP BRINE CONTAMINATION

Table 15. Field Parameters and Dissolved Constituents of the Pease River Group.

Parameter/ Constituent	Concentration Range	Average Concentration
Temperature	17°C - 23°C	20°C
Specific Cond.	404 - 10,200 µmhos	3,327 µmhos
pH	6.6 - 8.4	7.2
Eh	58.2 - 163.7 mV	124.3 mV
Carbonate	0 mg/l	0 mg/l
Bicarbonate	51 - 672 mg/l	272 mg/l
Barium	<20 - 404 µg/l	22 µg/l
Bromide	0.15 - 3.64 mg/l	1.01 mg/l
Cadmium	Below Detect. Lim.	Below Detect. Lim.
Calcium	3 - 783 mg/l	450 mg/l
Chloride	9 - 2,224 mg/l	323 mg/l
Dissolved Solids	296 - 7,368 mg/l	2,615 mg/l
Fluoride	0.2 - 2.5 mg/l	0.7 mg/l
Hardness (as $CaCO_3$)	10 - 2,600 mg/l	1,455 mg/l
Iron	<20 - 880 µg/l	113 µg/l
Magnesium	1 - 224 mg/l	95 mg/l
Potassium	4 - 16 mg/l	8 mg/l
Sodium	14 - 1,560 mg/l	242 mg/l
Strontium	<200 - 12,000 µg/l	5623 µg/l
Sulfate	4 - 2,547 mg/l	1314 mg/l
Nitrate (as NO_3)	0.04 - 131.2 mg/l	34.2 mg/l
Alpha	<2 - 15 pCi/l	8.6 pCi/l
Beta	<4 - 10 pCi/l	6.9 pCi/l

Table 16.–Pease River Wells which Show Evidence of Deep Brine Contamination.

Well Number	Aquifer Codes	County
05-60-601	313WTRS	Collingsworth
29-07-902	318SAGL	Fisher
29-14-301	313BLIN	Fisher
29-32-721	318SAGL	Taylor

A total of 41 wells exceeded drinking water standards in one or more constituents: 41 wells exceeded the sulfate standard; 41 wells exceeded the dissolved solids standard; 27 wells exceeded the chloride standard; nine wells exceeded the nitrate standard; three wells exceeded the iron standard; two wells exceeded the fluoride standard; and one well exceeded the alpha radiation standard.

Clear Fork Group

A total of eight wells in two counties were sampled in three aquifers within the Clear Fork Group. The map showing the locations and a trilinear diagram for the wells sampled in 1991 are shown in Figure 22. A summary of the field parameters and dissolved constituents is found in Table 17.

After running the RRC program and examining the ionic ratios of the water-quality analyses, two wells show evidence of deep brine contamination (Table 18). Figure 23 shows the locations of each and their proximity to known oil and gas fields and known vegetation kill areas. Both of these wells are located near other wells which are known to be contaminated by salt water. These contaminated wells possibly represent further contamination as reported previously.

Six wells exceeded drinking water standards in one or more constituents: five wells exceeded the standard for nitrate; three wells exceeded the standard for sulfate; three wells exceeded the standard for dissolved solids; two wells exceeded the standard for chloride; and one well exceeded the standard for alpha radiation.

Wichita-Albany Group

A total of 16 wells in four counties were sampled in three aquifers within the Wichita-Albany Group. The map showing the locations and a trilinear diagram for the wells sampled in 1991 are shown in Figure 24. A summary of the field parameters and dissolved constituents is found in Table 19.

After running the RRC program and examining the ionic ratios of the water-quality analyses, 8 wells show evidence of deep brine contamination (Table 20). Figure 25 shows the locations of each and their proximity to known oil and gas fields and known vegetation kill areas. All of these wells with the exception of 3028701 in Taylor County are near oil fields or contaminated wells or springs. The three wells in Montague County are also near known areas of vegetative kills.

Table 17.– Field Parameters and Dissolved Constituents of the Clear Fork Group.

Parameter/ Consitutent	Concentration Range	Average Concentration
Temperature	19°C - 23°C	21°C
Specific Cond.	874 - 6,970 μmhos	2,547 μmhos
pH	6.7 - 7.3	7.0
Eh	59.8 - 207.8 mV	130.4 mV
Carbonate	0 mg/l	0 mg/l
Bicarbonate	190 - 395 mg/l	311 mg/l
Barium	<20 - 130 μg/l	73 μg/l
Bromide	0.47 - 4.13 mg/l	1.67 mg/l
Cadmium	Below Detect. Lim.	Below Detect. Lim.
Calcium	70 - 741 mg/l	226 mg/l
Chloride	20 - 1,147 mg/l	326 mg/l
Dissolved Solids	434 - 5,225 mg/l	1,643 mg/l
Fluoride	0.6 - 1.2 mg/l	0.8 mg/l
Hardness (as $CaCO_3$)	322 - 2,865 mg/l	956 mg/l
Iron	<20 - 105 μg/l	20 μg/l
Magnesium	26 - 247 mg/l	95 mg/l
Potassium	2 - 12 mg/l	7 mg/l
Sodium	36 - 606 mg/l	182 mg/l
Strontium	740 - 16,500 μg/l	9,556 μg/l
Sulfate	46 - 2,267 mg/l	582 mg/l
Nitrate (as NO_3)	26.4 - 180.5 mg/l	82 mg/l
Alpha	<2 - 48 pCi/l	15 pCi/l
Beta	<4 pCi/l	<4 pCi/l

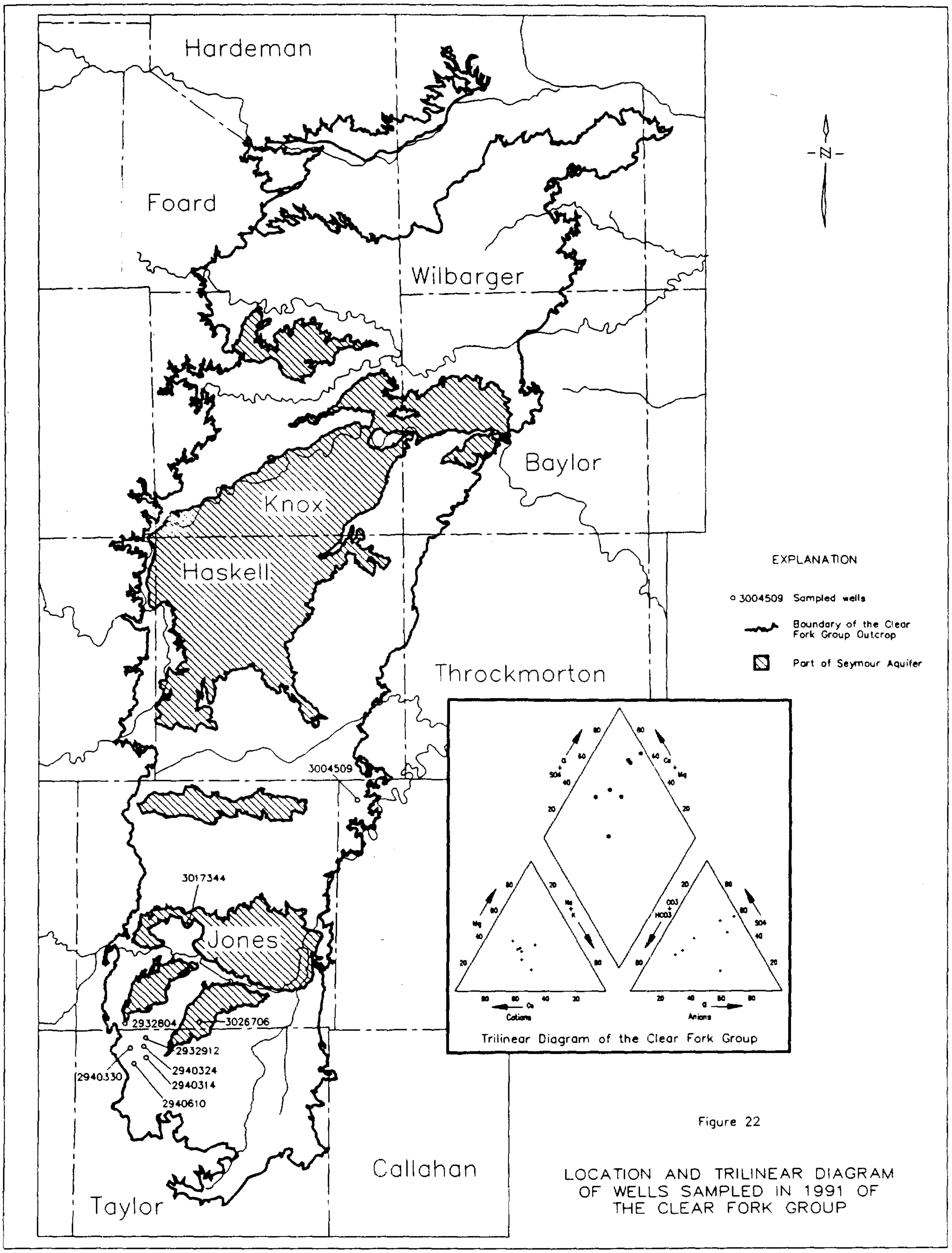


Figure 22

LOCATION AND TRILINEAR DIAGRAM OF WELLS SAMPLED IN 1991 OF THE CLEAR FORK GROUP

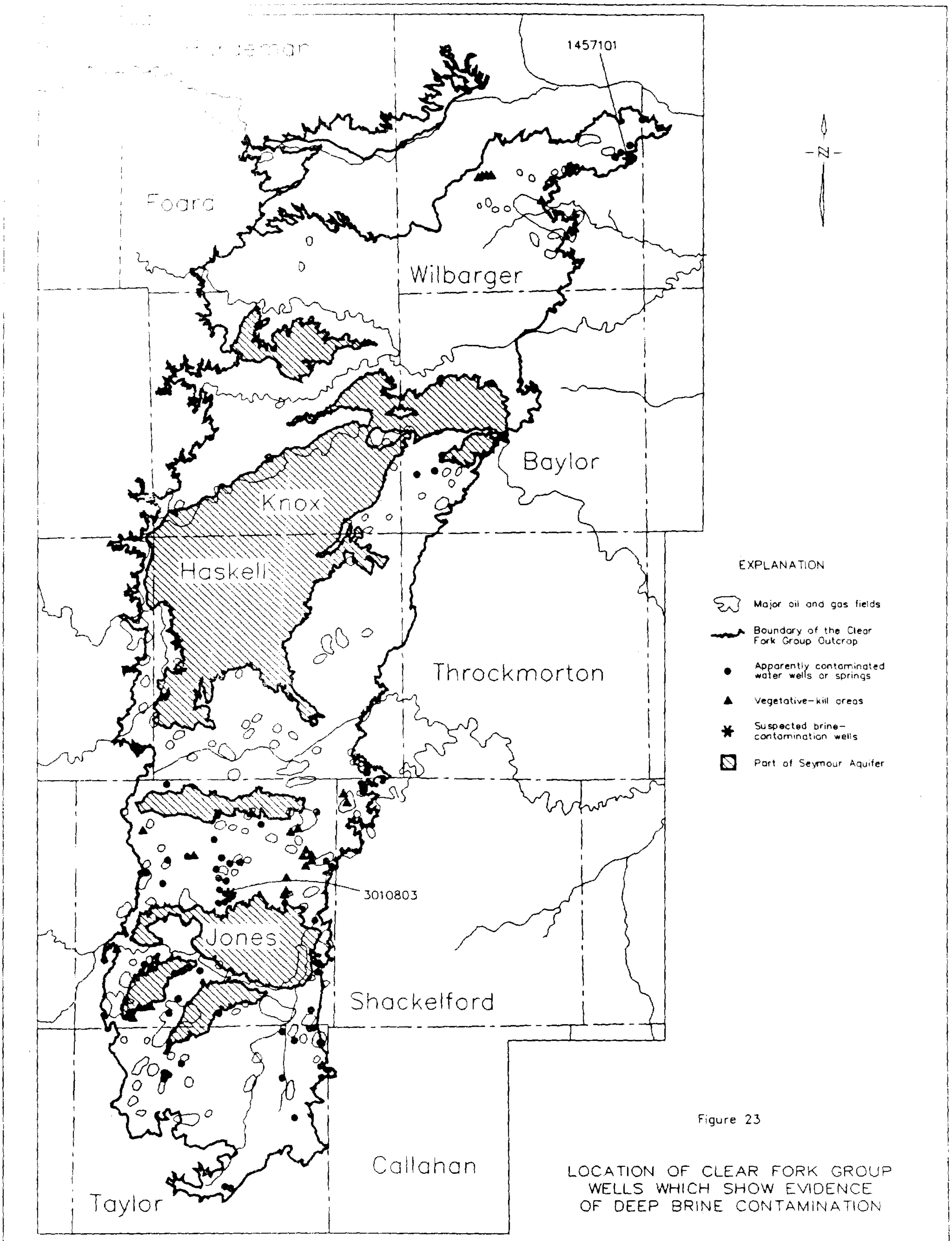


Figure 23

LOCATION OF CLEAR FORK GROUP WELLS WHICH SHOW EVIDENCE OF DEEP BRINE CONTAMINATION

Table 18.–Clear Fork Wells Which Show Evidence of Deep Brine Contamination

Well Number	Aquifer Codes	County
3010803	318VALE	Jones
1457101	318CLFK	Wilbarger

Eleven wells exceeded drinking water standards in one or more constituents: seven wells exceeded the standard for chloride; seven wells exceeded the standard for nitrate; six wells exceeded the standard for dissolved solids; three wells exceeded the standard for iron; two wells exceeded the standard for sulfate; two wells exceeded the standard for alpha radiation; and one well exceeded the standard for barium.

Cisco Group

A total of 70 wells in eight counties were sampled in eight aquifers within the Cisco Group. The map showing the locations and a trilinear diagram for the wells sampled in 1991 are shown in Figure 26. A summary of the field parameters and dissolved constituents is found in Table 21.

After running the RRC program and examining the ionic ratios of the water-quality analyses, six wells show evidence of deep brine contamination (Table 22). Figure 27 shows the locations of each and their proximity to known oil and gas fields and known vegetation kill areas. These wells are located near oil fields and near areas of known contaminated springs and wells and previous vegetative kill areas. Numerous studies and reports have shown that these counties have some of the worst cases of salt-water pollution in the bounds of the study area.

Thirty-eight wells exceeded drinking water standards in one or more constituents: 26 wells exceeded the standard for dissolved solids; 20 wells exceeded the standard for chloride; twelve wells exceeded the standard for iron; 11 wells exceeded the standard for nitrate; nine wells exceeded the standard for sulfate; eight wells exceeded the standard for fluoride; one well exceeded the standard for alpha radiation; and one well exceeded the standard for beta radiation.

Canyon Group

A total of 17 wells in five counties were sampled in five aquifers within the Canyon Group. The map showing the locations and a trilinear diagram for the wells sampled in 1991 are shown in Figure 28. A summary of the field parameters and dissolved constituents is found in Table 23.

After running the RRC program and examining the ionic ratios of the water-quality analyses, one well (2055311) shows evidence of deep brine contamination. Figure 29 shows the location of the well and its proximity to known oil and gas fields and known vegetation kill areas. This well is near oil fields which could have been a source of contamination.

Eleven wells in the Canyon Group exceeded drinking water standards in one or more constituents: six wells exceeded the standard for chloride; six wells exceeded the standard for dissolved solids; four wells exceeded the standard for iron; three wells exceeded the standard for fluoride; and one well exceeded the standard for nitrate.

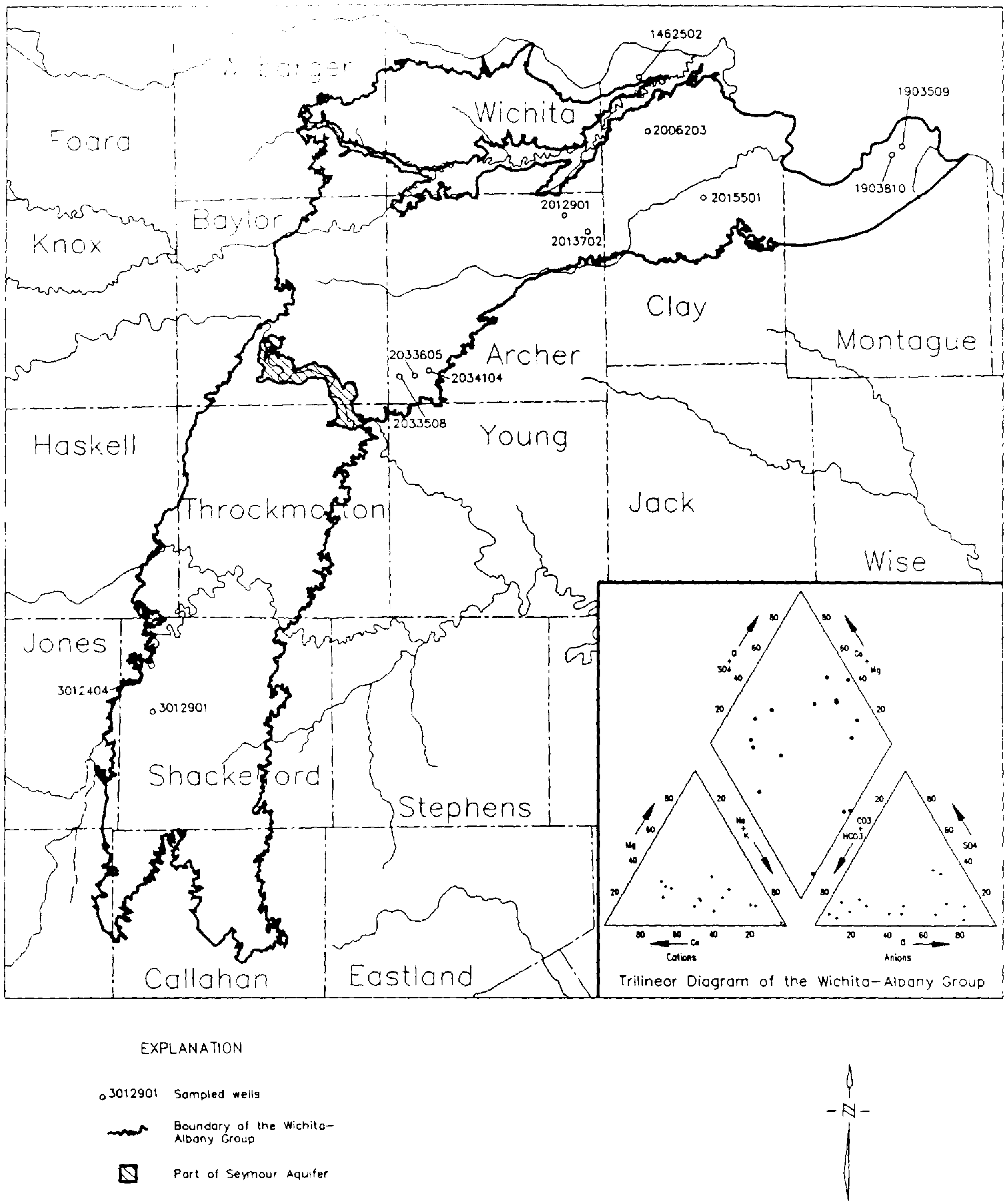


Figure 24

LOCATION AND TRILINEAR DIAGRAM OF WELLS SAMPLED IN 1991 OF THE WICHITA-ALBANY GROUP

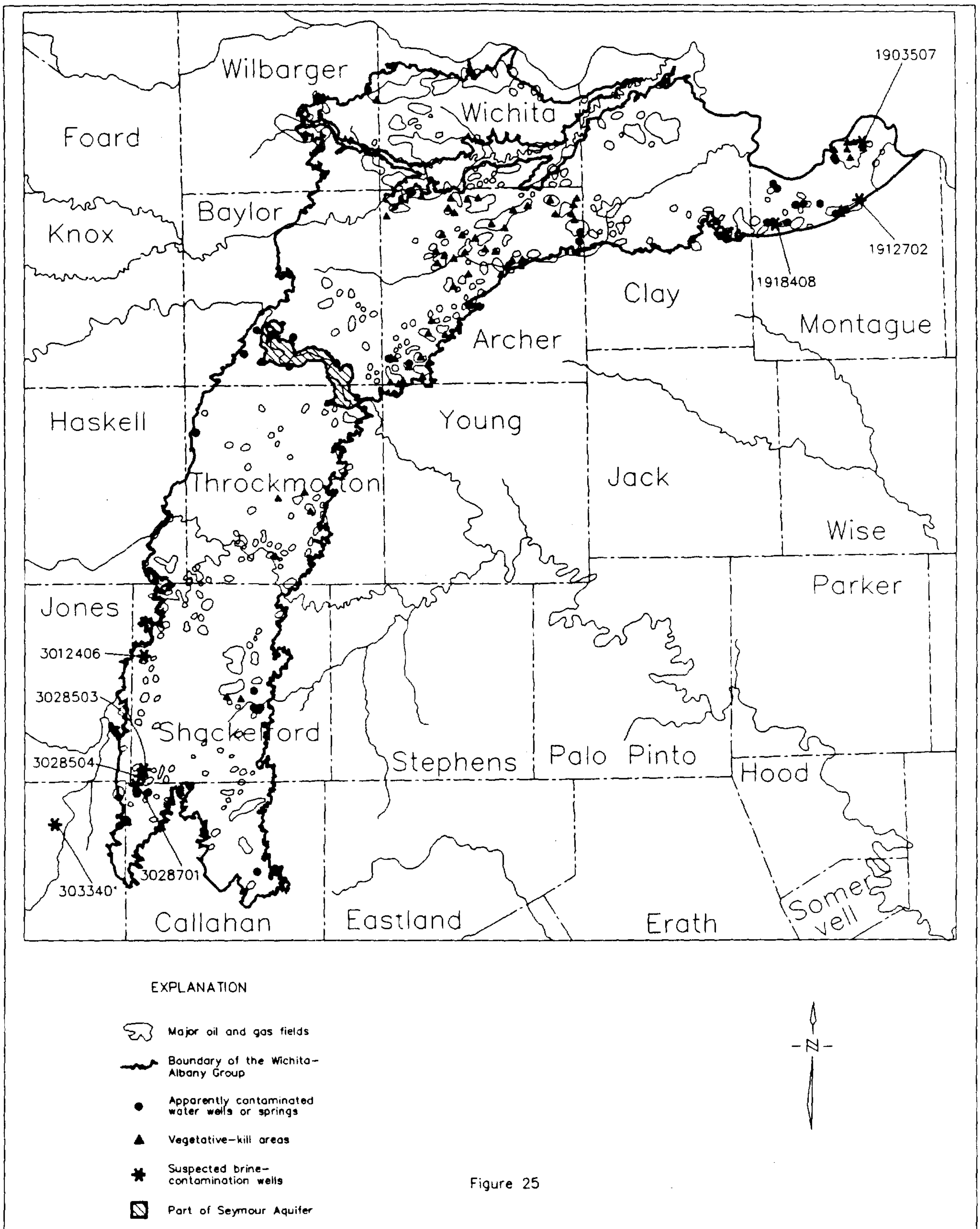


Figure 25

LOCATION OF WICHITA-ALBANY GROUP WELLS WHICH SHOW EVIDENCE OF DEEP BRINE CONTAMINATION

Figure 26

LOCATION AND TRILINEAR DIAGRAM OF WELLS SAMPLED IN 1991 OF THE CISCO GROUP

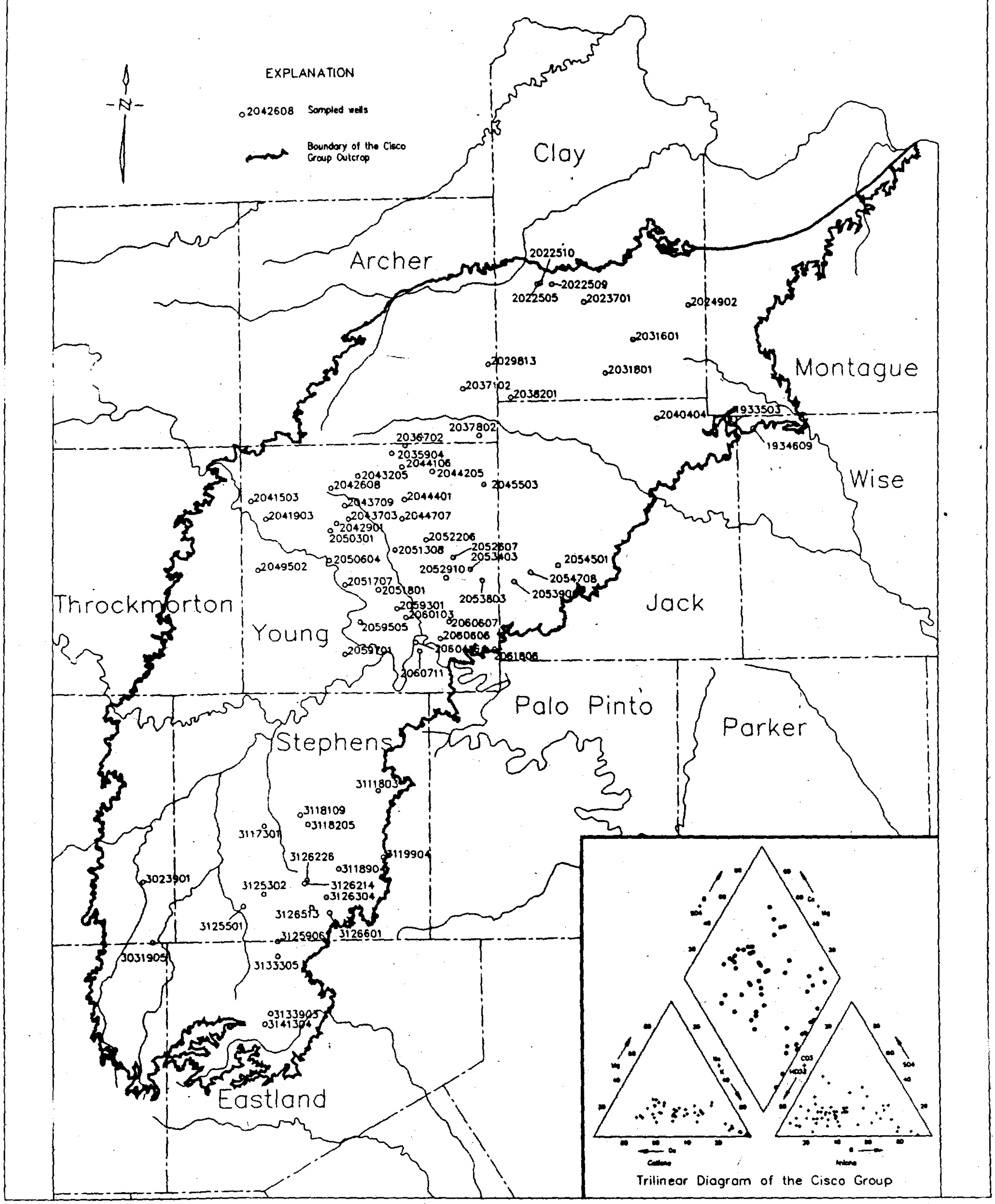


Figure 27

LOCATION OF CISCO WELLS WHICH SHOW EVIDENCE OF DEEP BRINE CONTAMINATION

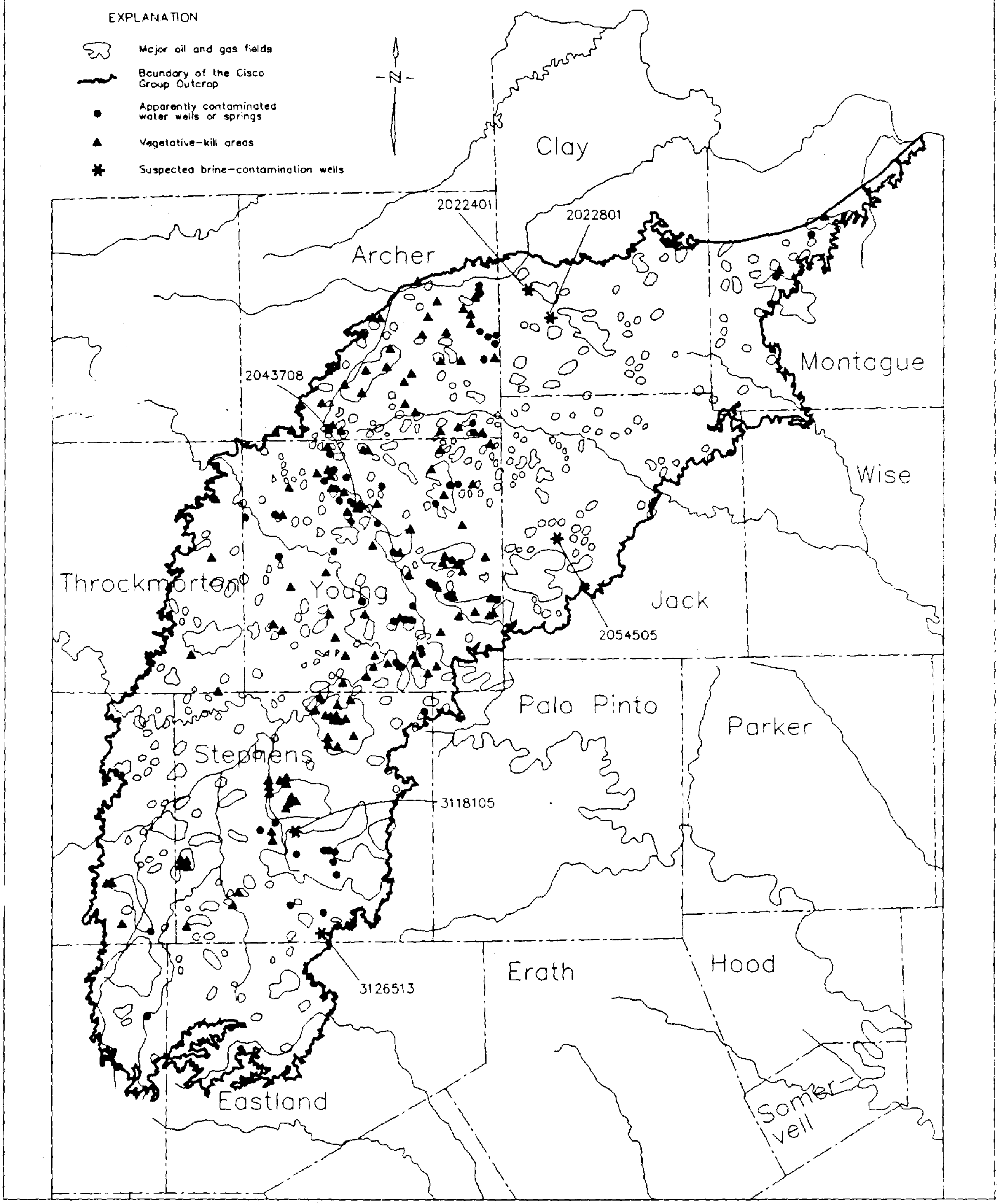


Table 19.--Field Parameters and Dissolved Constituents of the Wichita-Albany Group.

Parameter Constituent	Concentration Range	Average Concentration
Temperature	17°C - 21°C	19°C
Specific Cond.	428 - 8,410 μmhos	2,350 μmhos
pH	7.1 - 8.7	7.5
Eh	-78.5 - +218.5 mV	+111.2 mV
Carbonate	O - 12 mg/l	1 mg/l
Bicarbonate	194 - 541 mg/l	370 mg/l
Barium	<20 - 7,580 μg/l	638 μg/l
Bromide	<0.1 - 17.68 mg/l	2.86 mg/l
Cadmium	Below Detect. Lim.	Below Detect. Lim.
Calcium	1 - 518 mg/l	121 mg/l
Chloride	8 - 3632 mg/l	679 mg/l
Dissolved Solids	271 - 5,745 mg/l	1,625 mg/l
Fluoride	0.1 - 1.1 mg/l	0.6 mg/l
Hardness (as $CaCO_3$)	3 - 2,189 mg/l	510 mg/l
Iron	<20 - 1,610 μg/l	177 μg/l
Magnesium	0 - 218 mg/l	51 mg/l
Potassium	1 - 23 mg/l	5 mg/l
Sodium	25 - 1,250 mg/l	410 mg/l
Strontium	<200 - 39,200 μg/l	3,805 μg/l
Sulfate	9 - 837 mg/l	151 mg/l
Nitrate (as NO_3)	<0.04 - 65.2 mg/l	29.2 mg/l
Alpha	<2 - 35 pCi/l	8.8 pCi/l
Beta	<4 - 4.5 pCi/l	<4 pCi/l

Table 20. –Wichita-Albany Wells which Show Evidence of Deep Brine Contamination.

Well Number	Aquifer Codes	County
1903507	318WCHT	Montague
1912702	318WCHT	Montague
1918408	318WCHT	Montague
3012406	318LDRS	Shackelford
30Z8503	318LDRS	Shackelford
3028504	318LDRS	Shackelford
3028701	318LDRS	Shackelford
3033401	318LDRS	Taylor

Table 21. –Field Parameters and Dissolved Constituents of the Cisco Group.

Parameter/ Constituent	Concentration Range	Average Concentration
Temperature	17°C - 23°C	20°C
Specific Cond.	320 - 7,030 μmhos	1589 μmhos
pH	5.9 - 8.8	7.3
Eh	-252.8 - +220.4 mV	+39.4 mV
Carbonate	0 - 19 mg/l	0 mg/l
Bicarbonate	66 - 737 mg/l	400 mg/l
Barium	<20 - 526 μg/l	64 μg/l
Bromide	<0.1 - 8.73 mg/l	1.3 mg/l
Cadmium	Below Detect. Lim.	Below Detect. Lim.
Calcium	1 - 341 mg/l	91 mg/l
Chloride	7 - 2,009 mg/l	267 mg/l
Dissolved Solids	167 - 3,740 mg/l	1,014 mg/l
Fluoride	0.1 - 4.5 mg/l	1.1 mg/l
Hardness (as CaCO~)	4 - 1,238 mg/l	325 mg/l
Iron	<20 - 2,710 μg/l	184 μg/l
Magnesium	0 - 107 mg/l	25 mg/l
Potassium	1 - 9 mg/l	4 mg/l
Sodium	8 - 1,300 mg/l	251 mg/l
Strontium	<200 - 10,500 μg/l	1,545 μg/l
Sulfate	12 - 963 mg/l	158 mg/l
Nitrate (as NO~)	<0.04 - 303.4 mg/l	24.2 mg/l
Alpha	<2 - 35 pCi/l	3.4 pCi/l
Beta	<4 - 51 pCi/l	6.3 pCi/l

Table 22. –Cisco Wells which Show Evidence of Deep Brine Contamination.

Well Number	Aquifer Code	County
2022401	321CSCO	Clay
2022801	321CSCO	Clay
2054505	321CSCO	Jack
3118105	321TRFT	Stephens
3126513	321TFGM	Stephens
2043708	321HPVL	Young

Table 23. –Field Parameters and Dissolved Constituents of the Canyon Group.

Parameter/ Constituent	Concentration Range	Average Concentration
Temperature	19°C - 25°C	21°C
Specific Cond.	487 - 3,680 µmhos	1,395 µmhos
pH	6.8 - 8.8	7.8
Eh	-267.3 - +104.4 mV	-30.8 mV
Carbonate	0 - 31 mg/l	3 mg/l
Bicarbonate	204 - 697 mg/l	273 mg/l
Barium	<20 - 234 µg/l	84 µg/l
Bromide	<0.1 - 3.68 mg/l	0.83 mg/l
Cadmium	Below Detect. Lim.	Below Detect. Lim.
Calcium	19 - 180 mg/l	53 mg/l
Chloride	6 - 842 mg/l	201 mg/l
Dissolved Solids	312 - 2,162 mg/l	864 mg/l
Fluoride	0.2 - 4.5 mg/l	1.3 mg/l
Hardness (as CaCO~)	5 - 535 mg/l	183 mg/l
Iron	<20 - 1,370 µg/l	184 µg/l
Magnesium	1 - 51 mg/l	13 mg/l
Potassium	1 - 7 mg/l	4 mg/l
Sodium	6 - 896 mg/l	273 mg/l
Strontium	<200 - 7,020 µg/l	1,355 µg/l
Sulfate	12 - 278 mg/l	80 mg/l
Nitrate (as NO~)	<0.04 - 44.9 mg/l	4.2 mg/l
Alpha	<2 - 6 pCi/l	2.8 pCi/l
Beta	<4 - 9.9 pCi/l	6.3 pCi/l

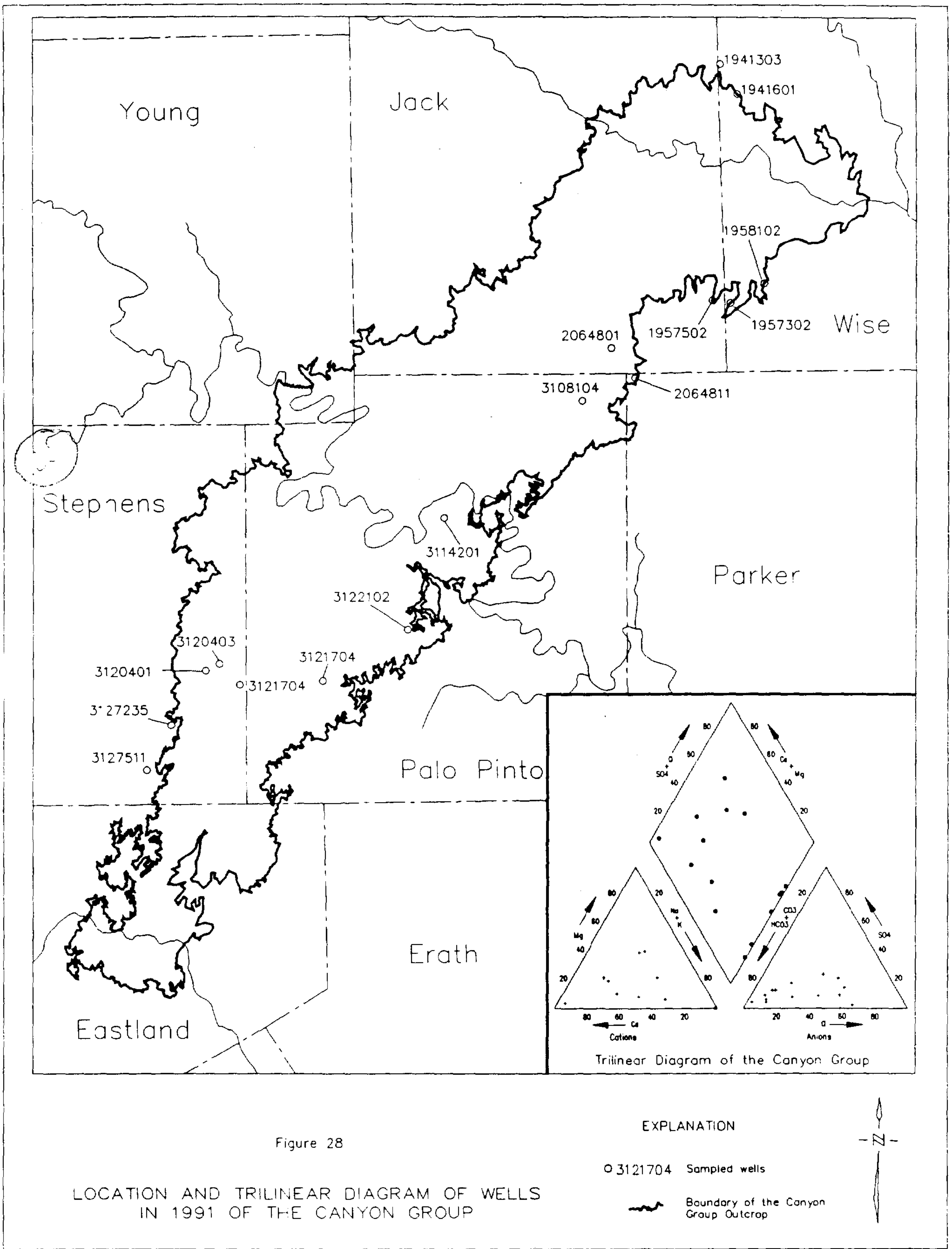


Figure 28

LOCATION AND TRILINEAR DIAGRAM OF WELLS IN 1991 OF THE CANYON GROUP

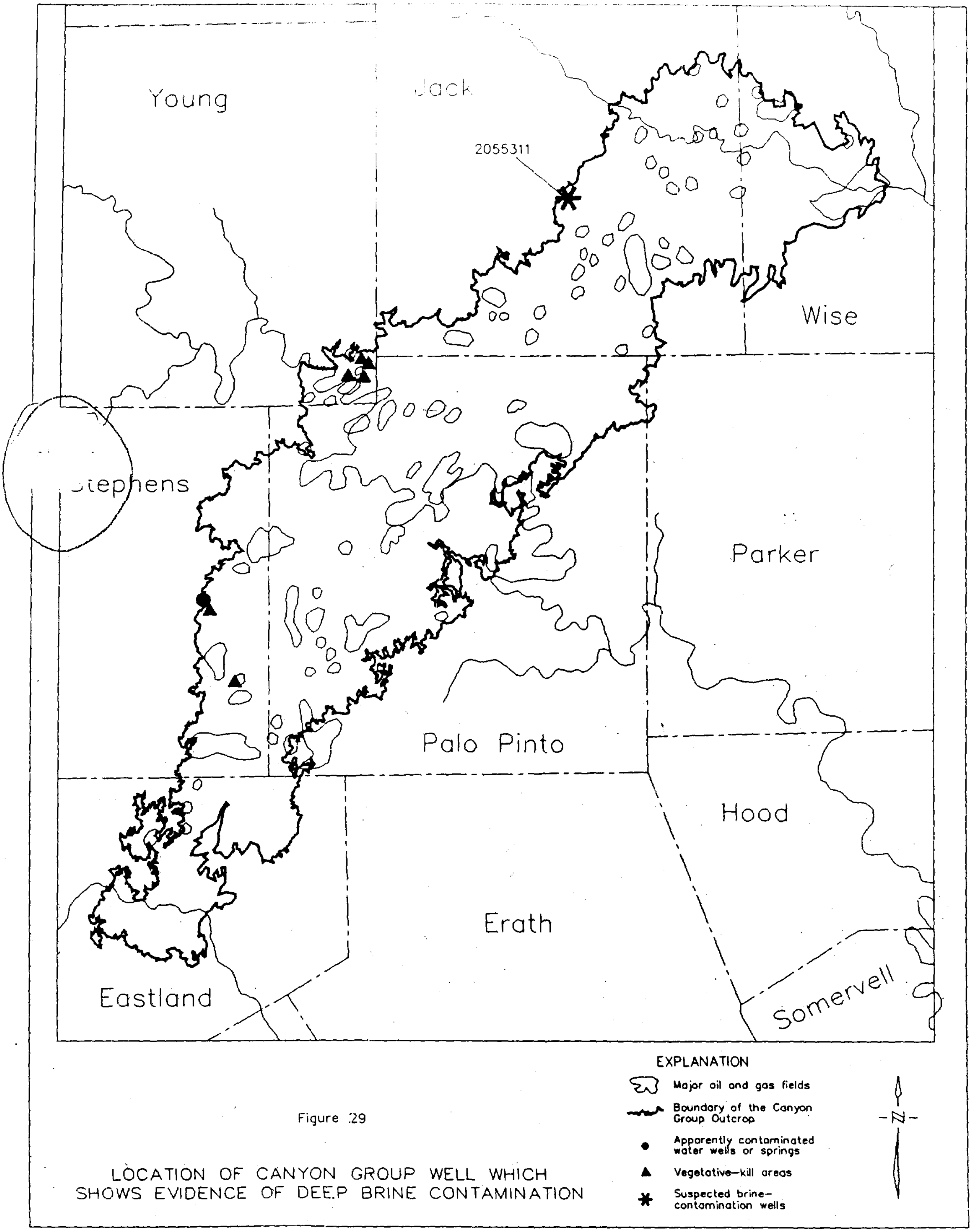


Figure 29

LOCATION OF CANYON GROUP WELL WHICH SHOWS EVIDENCE OF DEEP BRINE CONTAMINATION

Strawn Group

A total of three wells in one county were sampled in two aquifers within the Strawn Group. After running the RRC program and examining the ionic ratios of the wells, none of the wells shows evidence of deep brine contamination.

Appendix B
Alternate Technology - Desalination

APPENDIX B

Alternate Technology – Desalinization

The program to convert brackish and saline water resources to fresh water differs from other water development programs because it can develop an entirely new source of fresh water to meet municipal and industrial demands. Water containing 50,000 mg/l TDS is generally considered the upper limit of water that is economically feasible to desalt for municipal and industrial purposes.

The need for additional fresh water supplies has led more municipal and industrial users to consider desalting the hugh known supplies of inland brackish and saline water. Recent research and development activities in desalting processes, especially reverse osmosis and electrodialysis, have reduced the cost of converting brackish and saline water to fresh water so that these processes are now being used commercially to provide municipal and industrial supplies of fresh water at about 650 locations in the United States, including approximately 80 in Texas, and about 1,600 other locations around the world.

A 1964 state-federal study of the potential contribution of desalting technology to future water supplies in eleven cities revealed that the unit cost of desalted water was less than or about the same as that of developing the most feasible alternative fresh-water supplies. Another study showed that saline ground water in several regions of West Texas can be desalted at reasonable costs to partially fulfill future needs for municipal and industrial supplies.

Desalting Processes

Desalting is the process by which brackish and saline water is converted into fresh water by removal of dissolved inorganic material, and in some cases by the additional removal of suspended material, organic material, bacteria, and viruses. In Texas the predominant methods of removing dissolved and suspended material include phase change, such as distillation, and membrane processes, such as electrodialysis and reverse osmosis. Ion exchange, a chemical desalting process, is being used primarily by industry in the State following conventional water treatment or a desalting process to remove specific inorganic ions that may be detrimental to the water's use if not removed.

Distillation

Distillation is the oldest of the desalination processes and is most widely used for desalting sea water. Distillation processes are based on the insolubility of salts in steam; during vaporization the salts remain in the distilland (brine) as the vapor flows to the condenser to become product water. Product water salinity depends more on plant design than on feed water salt concentration.

Many of these plants operate in conjunction with power plants. This dual purpose operation is advantageous from the standpoint of energy saved and shared costs of facilities and personnel. Combining saline water conversion with electric-power generation shows promise as an economical method of producing large quantities of fresh water.

Electrodialysis

In the electrodialysis process, brackish or slightly saline water flows between alternating cation permeable and anion permeable membranes. A direct electric current provides the motive force to drive the salt ions through the membranes and leave fresh water behind. Electrodialysis is a well developed process with a history of 20 years operation on brackish water supplies. Advantages of the process include: a well developed technology including equipment and membranes; efficient removal of most inorganic constituents; a waste brine that contains only salts removed plus a small amount of acid used in some cases for pH control; the ability to utilize waste heat to reduce energy requirements; and a reversing electrodialysis system which reduces the amount of chemicals needed for scale control.

Reverse Osmosis

In its most simple presentation, reverse osmosis is a membrane process that acts as a molecular filter to remove up to 99 percent of the dissolved minerals, 97 percent of the dissolved organics, and 98 percent of the biological and colloidal matter from brackish and saline water. The reverse osmosis process has also been intensively developed in the last 20 years. Advantages of this process include: the very high removal rate of inorganic and organic material, turbidity, bacteria, and viruses; removal efficiencies and energy consumption remain very stable over the range of dissolved solids present in most brackish waters; the ability to utilize some waste heat to reduce energy requirements; and waste brine contains only salt removed plus a small amount of chemicals added for pH and scale control.

Current Desalting Uses in Texas

Desalting Plants Inventory Report No. 7, released in 1981, listed a total of 71 desalting plants in Texas, excluding ion exchange systems, producing more than 17.1 million gallons per day of water for public supply, industrial uses, and electrical power generating plant boiler feedwater by both membrane and phase-change processes. By 1991, there were 89 desalting units at 77 locations in the State producing more than 34.6 million gallons per day for the same purposes and by the same processes as 1981. Sixteen of those units are electrodialysis (ED) or electrodialysis reversal (EDR), 62 are reverse osmosis (RO) and 11 are of the phase-change or distillation process. Of the 89 plants inventoried in 1991, 14 produced 10,168,000 gallons per day (gpd) for municipal use, 50 plants produced 21,040,000 gpd for industrial use, and 25 plants produced 3,451,000 gpd for power plant boiler feedwater.

Potential Desalting Uses in Texas

Desalting, by either the reverse osmosis or electrodialysis method, may prove to be the most economically feasible means that some municipal water systems have available to provide needed additional water and/or bring them into compliance with the standards of the Safe Drinking Water Act Amendments. Several factors must be considered in order to define those areas of Texas in which desalting technology has the potential of being applied for municipal and industrial water supplies. There must be a readily available supply of brackish or saline surface or ground water in sufficient quantity to meet the need; the desalting plant must be determined to be economically feasible when compared to available conventional water supplies; a method of brine disposal must be available; and an energy source must be available.

Preliminary information indicates that the above conditions generally prevail throughout most of West Texas, the Panhandle, west-central Texas, the Gulf Coast, and especially the Lower Rio Grande Valley. Although sufficient data are not available to determine the quantities of ground water that can be produced by a specific well or in a specific area, it is assumed that significant quantities can be developed to supply desalt plants in most areas of the State where brackish and saline ground water occur.

Cost of Desalting

Several factors can influence the cost of desalted water such as the chemical quality of the raw water, energy costs, the size of the plant, and disposal of the waste brine. Table 24 gives ranges of total annual costs in dollars per thousand gallons of product water under various conditions. These costs include all design, engineering, and equipment costs necessary to complete an operable plant, O&M and amortization of capital for 20 years at 11 percent interest.

Table 24.--Desalting Cost Estimates for a Plant Producing from 1.0 to 10.0 MGD in Texas [1]

Desalting Process [2]	Feedwater Quality Range (mg/l TDS)	Possible Feedwater Recovery (%)	Energy Cost [3] $/1,000 gal.	Total Annual Cost [4] $/1,000 gal.
RO	1,5000-5,000	75-85	0.35-0.50	1.00-2.50
RO	5,000-20,000	50-75	0.59-1.20	2.00-4.00
RO	20,000-35,000	30-50	1.20-1.90 [5]	3.00-5.50
RO	35,000-45,000	30	1.25-1.90 [5]	3.00-5.50
VTE-VC	35,000-50,000	90	1.30-1.50	4.50-5.50 [6]

1 Data from National Water Supply Improvement Association.
2 RO = Reverse Osmosis, VTE-VC = Vertical Tube Evaporation-Vapor Compression.
3 RO using electricity @ $0.05/KWH, VTE-VC using natural gas @ 3/million BTU.
4 Total annual cost includes manufactured equipment, labor, housing electrical equipment and instrumentation, miscellaneous items needed to complete unit, yard piping, engineering and other costs necessary to furnish a complete system ready to operate, operation and maintenance, and amortization of capital for 20 years at 11 percent interest. It does not include well field or intake structure, transmission lines to the plant, cost of land, brine disposal, and taxes.
5 Cost range includes plants with and without energy recovery systems.
6 Dual or multiple purpose plants would have lower costs.

Municipal desalting plants, like conventional water supply and treatment facilities, are financed through the sale of bonds and grants and loans from Federal and State agencies like the Texas Water Development Fund.

In addition, many companies offer municipal and industrial desalt systems on a lease-purchase arrangement thereby eliminating the need for bond issue, reducing the needed amount of "up-front" capital, and substantially reducing the amount of time to bring needed supply and quality improvements on line. Most desalt plants require less than one year from ground breaking to startup.

Brine Disposal

One of the most important considerations of a desalting system is the disposal of the waste brine stream that results from the process. The various methods employed can range from very expensive to potential income generators. The method selected is usually designed on site-specific basis and the most feasible and environmentally sound choice may be one or a combination of these depending on local conditions and brine quality.

Many brackish and saline waters contain elements or compounds that, when concentrated as in desalting plant brine waste, could be economically extracted and marketed. In these cases, a new industry could be established at or near the desalt plant to receive the brine as the raw material for processing. Potential products for extraction include bromine, chlorine, caustic soda, gypsum, iodine, and magnesium compounds such as magnesite.

Potential Desalting Development in Texas

A growing number of municipal and industrial water supplies in Texas are investing in desalting as a means to provide future water supplies for their customers. This interest is in response to the increasing costs of conventional water supply development and reduced availability in some areas of the State, especially during drought periods similar to that experienced in the summers of 1980 and 1984.

Data are currently available to delineate by location and quality the known brackish and saline ground and surface water in the State. However, additional studies are needed to determine the quantities available for development at various locations as well as the locations and quantities of wastewater available for municipal and industrial purposes through application of desalting technology.