Report 319

Evaluation of Water Resources in Part of Central Texas

January 1990

Texas Water Development Board

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by

Bernard Baker, Geologist
Gail Duffin, Geologist
Robert Flores, Geologist
and
Tad Lynch, Geologist

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CONCLUSIONS

The study area is within the central Texas region which lies in the Brazos, Colorado, and Trinity River basins and includes all or parts of Bell, Bosque, Brown, Burnet, Callahan, Comanche, Coryell, Eastland, Erath, Falls, Hamilton, Hill, Lampasas, Limestone, McLennan, Milam, Mills, and Somervell Counties.

The geologic formations underlying the study area range in age from Paleozoic rocks to Recent alluvium. The principal water-bearing formations are the Trinity Group's Antlers, Travis Peak, and Paluxy Formations, and the Woodbine Group, all of Cretaceous age. The Travis Peak is present as a water-bearing unit in most of the study area and contains the Hensell and Hosston Members which are the two most important artesian aquifers.

In 1985 there was a little less than 81,000 acre-feet of ground water pumped from all aquifers in the study area, with a little less than 77,000 acre-feet of ground water pumped from the Trinity Group aquifer. Irrigation accounted for about 56 percent of all ground water pumped in the study area, principally in Callahan, Comanche, Eastland, and Erath Counties.

A serious problem associated with the development of ground water from the Trinity Group aquifer is the decline of artesian pressure in areas of large ground-water withdrawals. A regional cone of depression exists in McLennan County centered around the Waco area with two localized cones of depression centered at the town of Lacy-Lakeview and at the Cities of Woodway, Hewitt, and Robinson. The larger decline, in the Woodway area has occurred over the last eight years with an average decline of over 50 feet per year. Moderate declines of 12 feet per year since 1967 have occurred in the Lacy-Lakeview area. Since 1967, water levels have declined in Bell, Bosque, Falls, and Hill Counties. The concentration of public supply and industrial wells in these areas, the high rate of continuous ground-water withdrawal, and the relatively low permeability of the sands have caused rapid and large water-level declines.

Degradation of native ground water within the Antlers and Travis Peak Formations by contaminants from oil-field brines and organic material are problems in Brown, Callahan, Comanche, Eastland, and Erath Counties. The Glen Rose Formation contains highly mineralized water in some areas and is possibly a source of contamination to the underlying Travis Peak Formation due to interformational leakage. Several wells in western Coryell County and the City of Blum's well in northwestern Hill County are completed in the Hensell Member and exhibit high contents of sulfate, fluoride, chloride, and total dissolved solids that may be the result of leakage from the overlying Glen Rose. The deterioration of water quality for the City of Blum has occurred over a 26-year period and is associated with water-level declines in the Hensell.

The Woodbine Group yields good quality water at or near the outcrop; however, the residual sodium carbonate (RSC) and percent sodium generally limit its use for irrigation, while high iron and fluoride content restricts its use for public supply.

The projected water demands for the study area by the year 2010 total over 287,700 acre-feet. Existing surface reservoirs in the study area alone can supply 296,400 acre-feet of water under 2010 conditions, an amount greater than the projected demands. Nearly all of this water, however, is either currently owned or under contract to supply current and future needs in the study area and other parts of the Brazos River Basin. An additional 176,000 acre-feet of surface water could become available with the development of the proposed Lake Bosque and Paluxy Reservoir projects and with reallocation of storage in existing Lakes Waco and Whitney. Reallocation of existing and future surface-water supplies will need to be negotiated between entities facing water shortages and owners of surplus water supplies.

The amount of ground water currently pumped exceeds the estimated annual effective recharge to the Trinity Group aquifer. Because the ground-water demands exceed the recharge, the ground-water supply for the study area will continue to be drawn from storage within the aquifer. Although most areas in the study area have sufficient surface water to meet projected municipal and manufacturing needs through 2010, localized shortages could occur by 1990 largely due to limited availability from the Trinity Group aquifer.

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INTRODUCTION

Purpose

In 1985, the Texas Legislature recognized that certain areas of the State are experiencing, or will experience in the future, critical underground water problems. This study of ground-water conditions in part of central Texas is in response to the 1985 passage of House Bill 2 by the Sixty-ninth Texas Legislature which called for the identification and study of critical ground-water areas in the State. The purpose of this report is to describe the geohydrologic conditions of the Trinity Group and other aquifers and to identify problems related to pumpage over-drafts and contamination of ground water as they exist or are expected to occur.

Location and Extent

The location of the central Texas region as defined in this report is shown on Figure 1. The Region has an areal extent of approximately 10,340 square miles, and represents about 3.9 percent of the State's total area. The Region lies within the Brazos, Colorado, and Trinity River basins and includes all or parts of 18 counties--Bell, Bosque, Brown, Burnet, Callahan, Comanche, Coryell, Eastland, Erath, Falls, Hamilton, Hill, Lampasas, Limestone, McLennan, Milam, Mills, and Somervell. Consideration was given to only that portion of each county in which usable ground water is found within the Trinity Group aquifer.

For the purpose of this report, usable ground water is considered to be water containing less than 3,000 milligrams per liter (mg/l) dissolved solids.

Topography and Drainage

The topography of the study area is the result of stream erosion of relatively flat and gently eastward dipping sedimentary rock strata. Drainage is to the southeast, mainly by the Brazos River and its tributaries. The major tributaries include the Bosque, Paluxy, and Leon Rivers and their respective tributaries. A small portion of northeast Hill County is drained by tributaries of the Trinity River, and to the southwest, portions of northeast Brown, Mills, and southern Callahan Counties are drained by tributaries of the Colorado River. Elevations range from about 2100 feet along the Callahan divide in the western part of the area to about 300 feet along the Brazos River near the Falls-Milam County line.

The part of central Texas defined by the boundaries of the study area lies within the Coastal Plains and the North Central Plains physiographic provinces. The boundary between these two provinces is generally taken as the trace of the Balcones Fault Zone which extends north-south through central Bell, McLennan, and Hill Counties. East of the zone the Coastal Plains consist of a relatively flat undulating surface that slopes gently eastward. West of the Balcones Fault Zone, the Gulf Coastal Plain merges inland with the gently rolling and hilly topography of the central Texas highlands. The eastern margins of the North Central Plains physiographic province has been highly dissected by erosion. The province is characterized by gentle slopes of low relief along the eastern most margin, which merge westward into low rounded wooded hills of

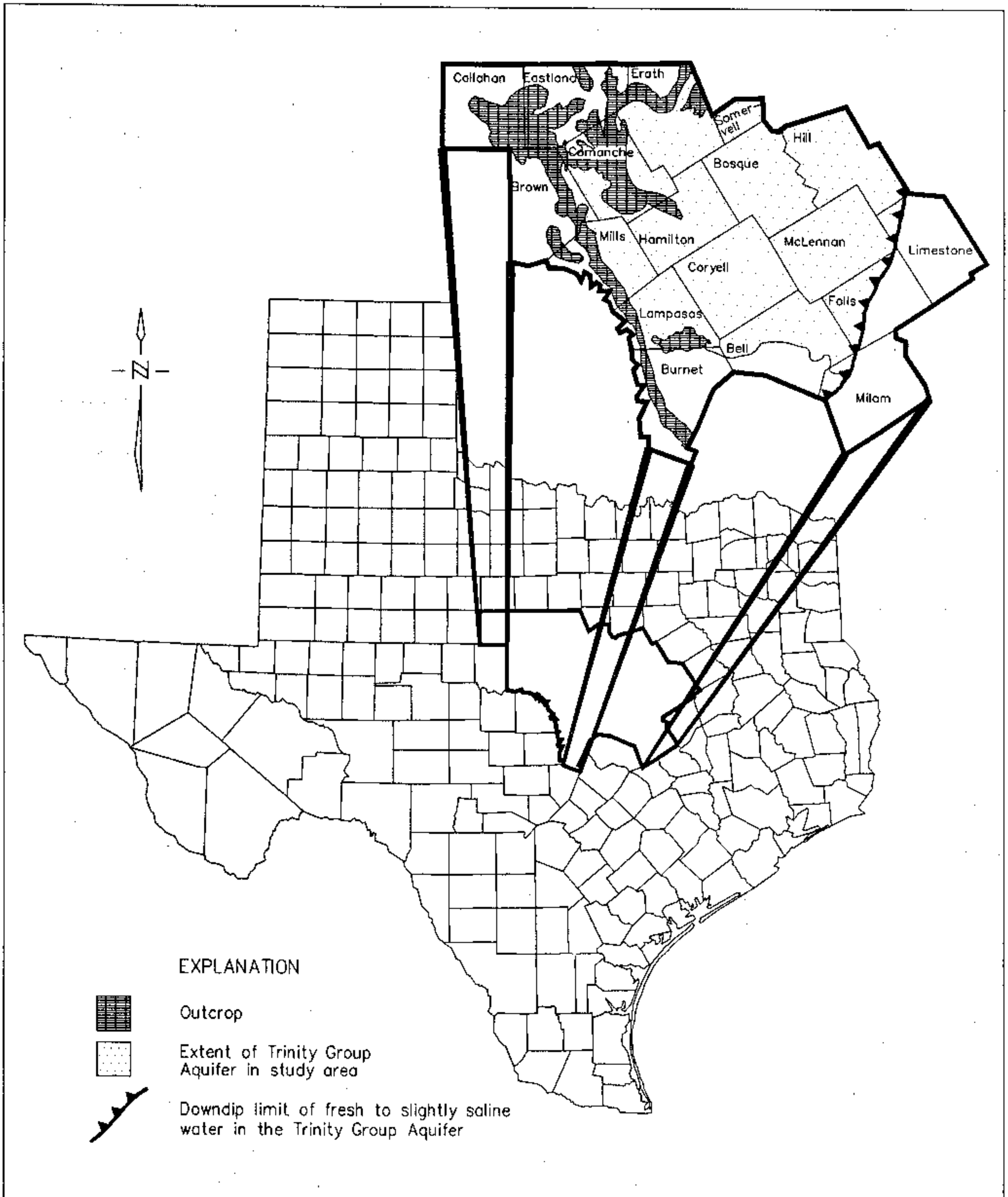


Figure 1

LOCATION OF STUDY AREA

moderate relief and then into rolling hilly topography along the interstream divides marked by occasional plateau remnants or mesas. Rough and steep hillsides and flat valleys border the winding, deeply entrenched streams near the Trinity Group outcrop regions creating one of the State's most scenic areas.

Climate

The climate of the study area is characterized by long hot summers and short mild winters. The average daily minimum temperature for January ranges from about 32°F in the northwest to 39°F in the southeast. The average annual precipitation ranges from about 24 inches in the northwest to about 36 inches in the eastern part of the study area.

Economy

The overall economy of the area encompassed by this study is based principally on agribusiness, manufacturing, and mineral production.

Agriculture production is extensive and varied; principal crops include peanuts, grain sorghum, corn, wheat and other small grains, hay, cotton, and pecans. Comanche County is the leading peanut producing county in the State. Livestock production includes dairy and beef cattle, sheep, goats, hogs, horses, and poultry. Dairying is practiced throughout the region and is an important industry. Erath County is the largest milk producer in the State.

Diversified manufacturing and various processing industries are generally located in or near the larger cities and towns in the area. Products include computer equipment, plastic goods, furniture, clothing, steel, glass, health care, and food products.

Natural resources in the area include oil, gas, sand, gravel, limestone, lime, and clay.

Marketing and distribution plays an important role in the economic vitality of the cities and towns. Waco, the largest city in the area, is the major distribution center for central Texas. Temple, the second largest city, is an important railroad, marketing, and distribution center.

Fort Hood, one of the largest military establishments in the nation, is located in Bell and Coryell Counties. Its military and civilian payroll adds substantially to the local economy.

Federal, State, and local government expenditures; extensive recreational facilities; and several educational institutions contribute to the area's economy.

Previous Investigations

The geology and ground-water resources in the central Texas area have been discussed in several, previously published reports whose investigations were conducted by the U.S. Geological Survey, Texas Water Development Board, Texas Bureau of Economic Geology, Baylor University, and private concerns. The most important ones are listed in the selected references at the end of this report.

The following ground-water investigations were used as principal references during the preparation of this report: Boone (1968), Klemt et al. (1975), Nordstrom (1987), Price et al. (1983), Rapp (1988), and Thompson (1967).

Acknowledgements

The Texas Water Development Board wishes to express its appreciation to the many well owners in the central Texas region who, for many years, have permitted access to their properties and permitted water levels in their wells to be measured and water samples taken for analysis, thereby providing the necessary database without which this report could not have been completed in a timely manner. Their help provided the valuable information necessary to evaluate the effects of pumpage on water levels and water quality.

Special thanks are extended to the Central Texas Study Area Advisory Committee. This committee was established by the Texas Water Development Board to provide a conduit through which interested and knowledgeable citizens in the Central Texas area could contribute to this study. The committee represented a wide range of interests in the area and included representatives of local government entities, public supply, industrial and agriculture-livestock users, public interest groups, and the education community. The committee members provided information on local ground-water conditions and problems, and contributed their valuable time in meeting with Board representatives and reviewing the preliminary draft of this report. The committee's contribution to this study is gratefully acknowledged.

This report was prepared under the general supervision of T.R. Knowles, Director of Planning, and Henry Alvarez, Chief of the Texas Water Development Board's Ground Water Section.

GEOHYDROLOGY

Geologic Framework

The geologic formations underlying the study area range in age from Paleozoic rocks to Recent alluvium. The most important water-bearing units are of Cretaceous age, specifically, the Antlers, Travis Peak, and Paluxy Formations of the Trinity Group, and the Woodbine Group. The central and north-central Texas regions includes several prominent geologic structures. The locations of these structures are shown in Figure 2. The most important structural features affecting the Trinity Group and subsequent geologic formations are the southeast regional dip of the pre-Cretaceous erosional surface and the extensive fault trends in the eastern part of the area. The outcrop area of the Trinity Group is illustrated in Figure 3. Figure 4 illustrates the stratigraphic nomenclature and structural relationships of the various formations and members of the Trinity Group aquifer. The stratigraphic relationship, approximate thickness, brief description, and water-bearing characteristics of the geologic units occurring in the central Texas region are summarized in Table 1. Geologic cross-sections portraying the structure and stratigraphic relationships of the various stratigraphic units are shown on Figures 4 and 5.

The geology of the study area has been presented in varying detail in several county and regional reports which are listed in the selected references at the end of this report. The two primary reports used during this study are "Ground-Water Resources of Part of Central Texas with Emphasis on the Antlers and Travis Peak Formations" by Klemt et al. (1978), and "Ground-Water Resources of the Antlers and Travis Peak Formations in the Outcrop Area of North-Central Texas" by Nordstrom (1987). These reports summarize the geologic history, structure, stratigraphic framework, and their effects on the occurrence of ground water in the study area. Consequently, it is beyond the scope of this report to present a detailed description of the geology of the region which would repeat much material previously published. It is hoped, however, that the abbreviated geologic information provided in Table 1 along with Figures 2 through 7 will be adequate to utilize the ground-water information presented in this report.

Source and Occurrence

The primary source of ground water in the study area is the infiltration of precipitation either directly in the outcrop or indirectly as seepage from streamflow. A small amount of the rainfall percolates downward under the force of gravity to the zone of saturation, where all the rock's voids contain water. Two characteristics of fundamental importance are porosity, or the amount of open space contained in the rock, and permeability, which is the ability of the porous material to transmit water. Fine-grained sediments such as clay and silt generally have high porosity, but have little or no permeability and consequently do not readily transmit water. Sand and gravel are usually both porous and permeable, the degree depending upon the size, shape, sorting, and amount of cementation of the grains. In limestone, igneous rocks, and tightly cemented or compacted rocks, porosity and permeability are controlled to some degree by the occurrence and extent of joints, crevices, and solution cavities. For a formation to be an aquifer, it must be porous, permeable, water-bearing, and yield water in usable quantities.

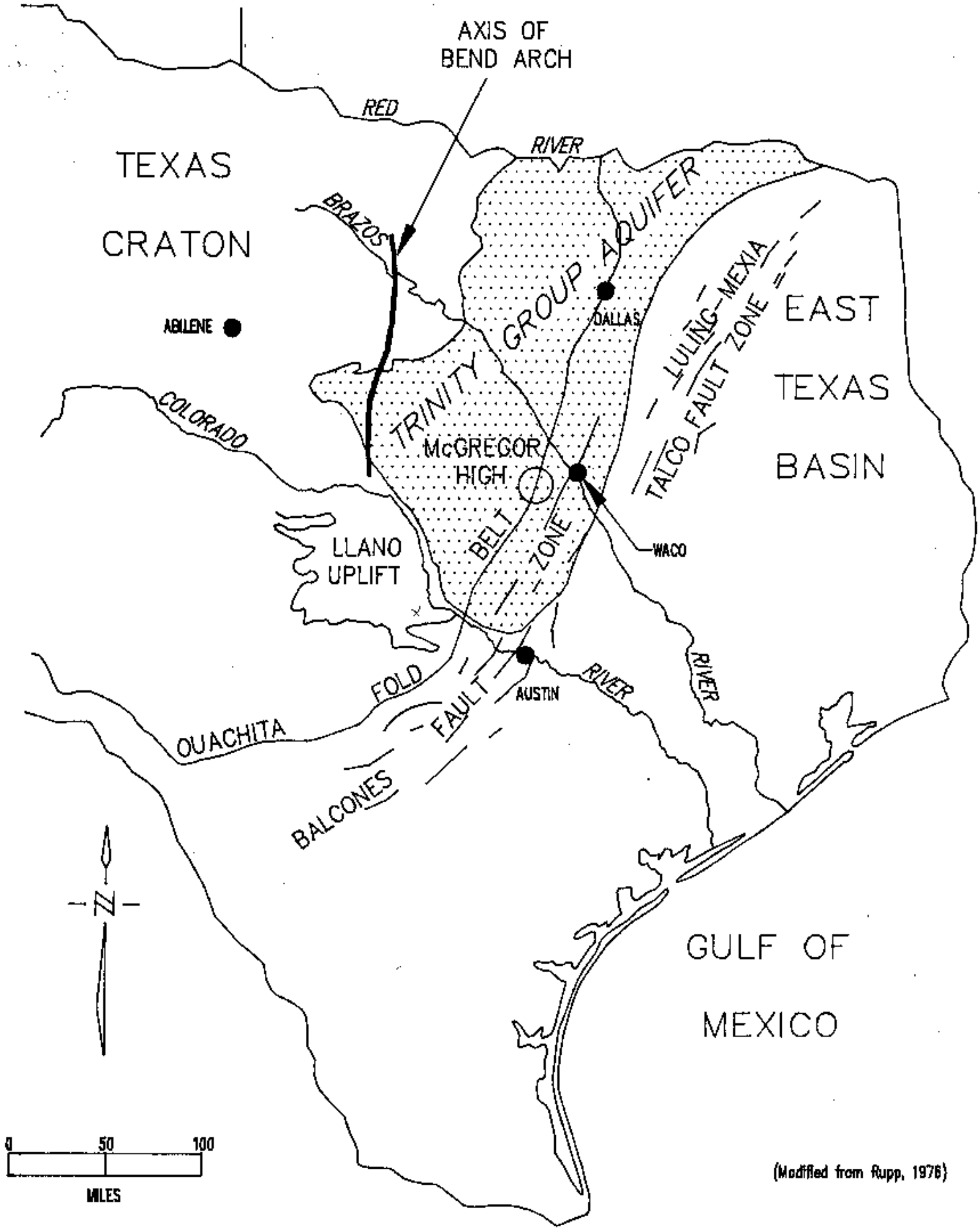


Figure 2

REGIONAL STRUCTURE AND EXTENT OF TRINITY GROUP AQUIFER IN CENTRAL TEXAS

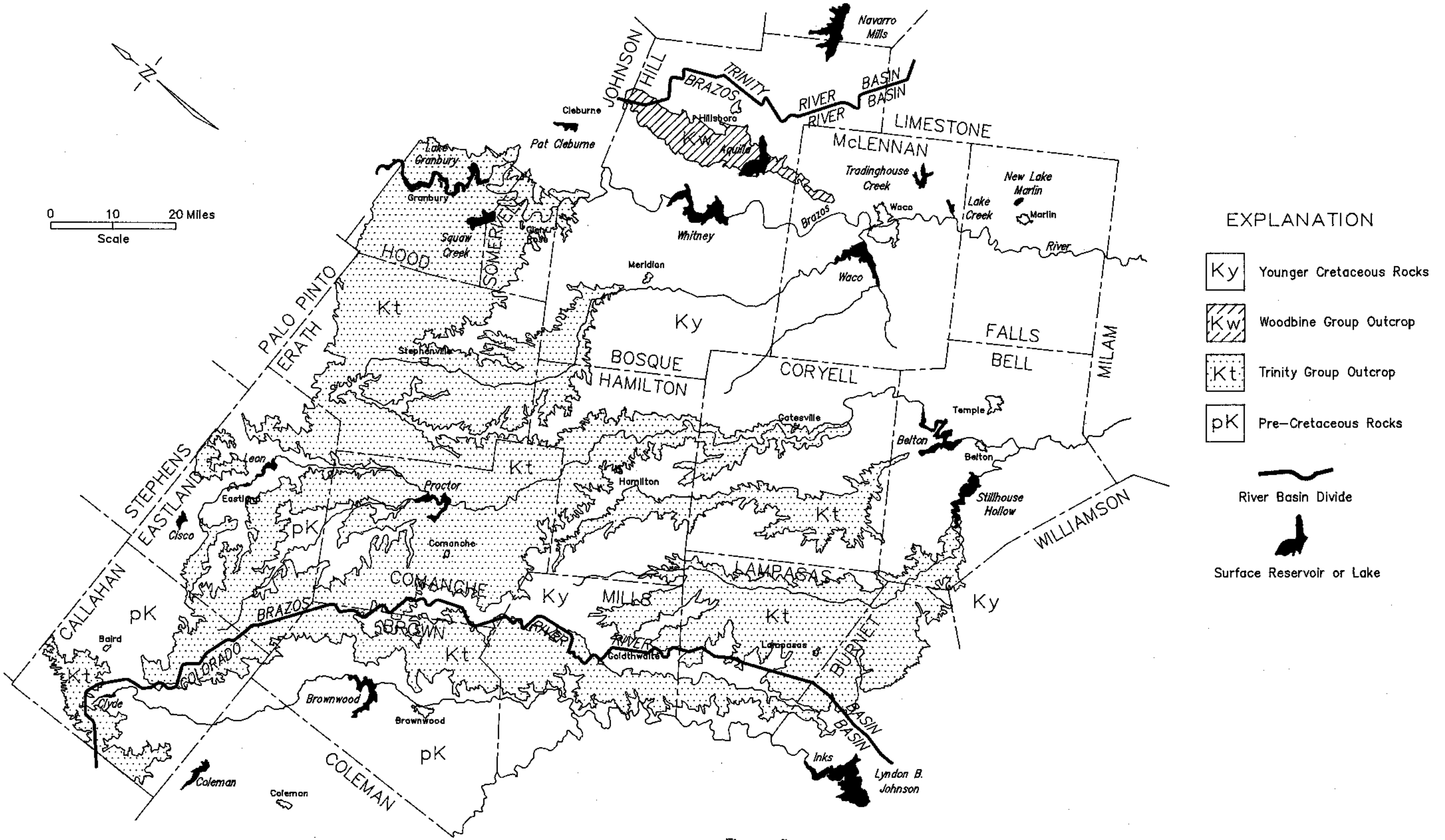


Figure 3

GEOLOGIC MAP

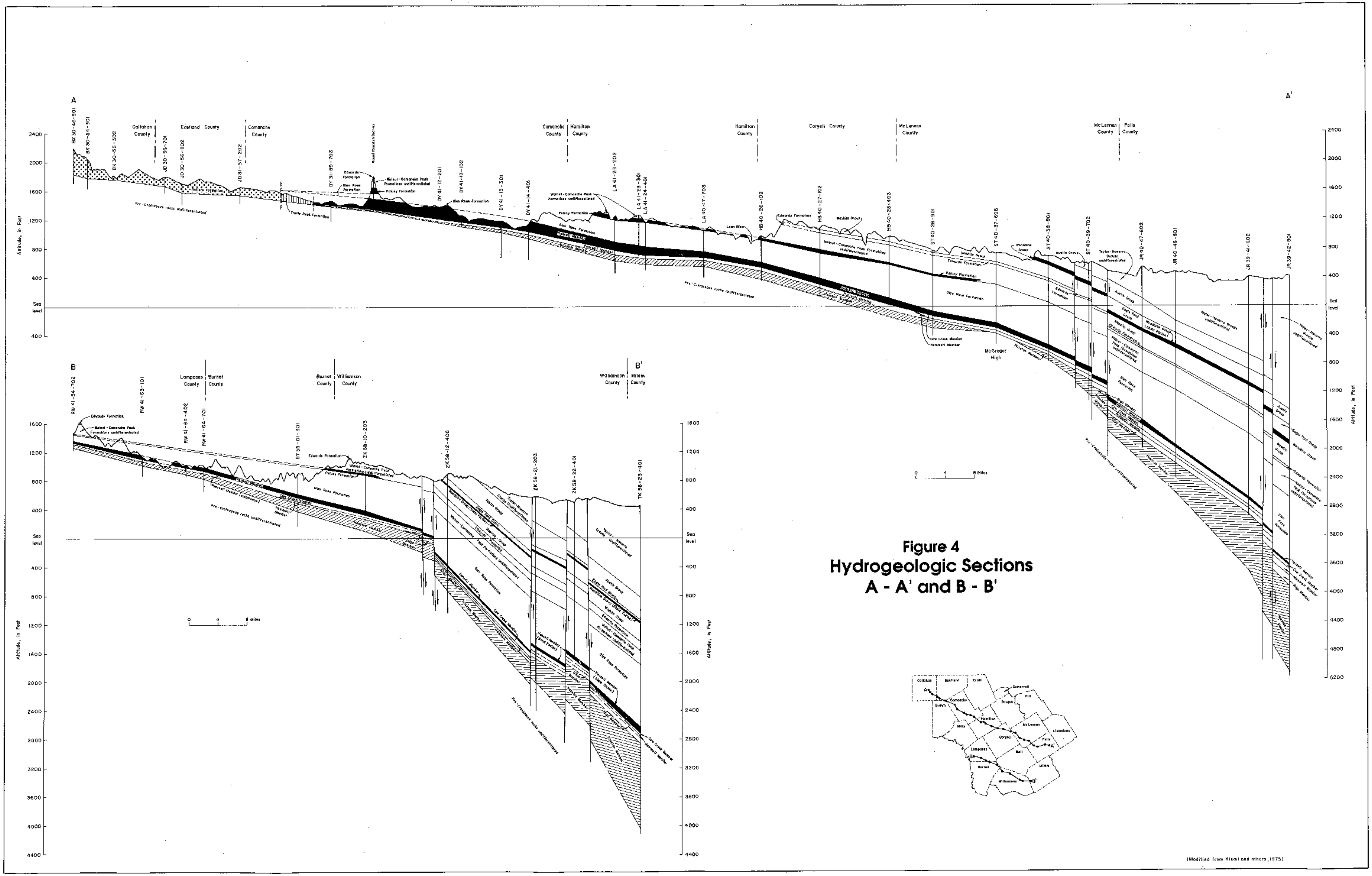


Figure 4
Hydrogeologic Sections
A - A' and B - B'

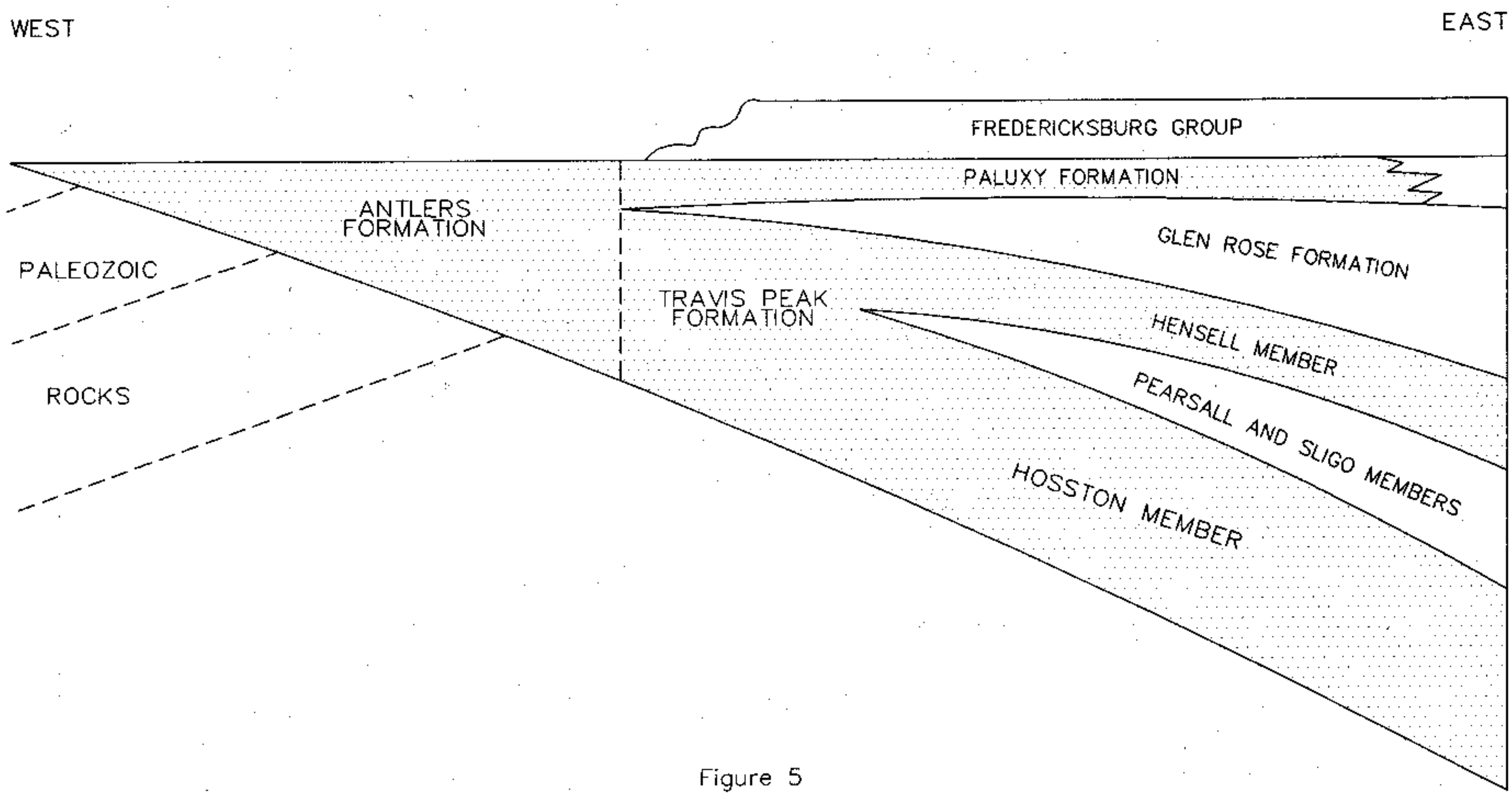


Figure 5

NOMENCLATURE OF THE TRINITY GROUP AQUIFER IN THE STUDY AREA

(Modified from Atchley, 1983, p.12)

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

System	Series	Group	Stratigraphic Unit	Hydrologic Unit	Approximate maximum thickness (feet)	Character of rocks	Water-bearing properties
Quaternary	Recent		Alluvium	Alluvium & terrace deposits	----	Mostly gravel, sand, silt, & clay.	Yields small to very large quantities of fresh to moderately saline water mostly along the Brazos River.
Cretaceous	Gulf				2,500	Shale, marl, & sand; limy shale and chalky limestone.	Locally yields small amounts of usable water.
	Gulf	Woodbine			250	Ferruginous sand, shale, sandstone, clay, & some lignite & gypsum.	Yields small to moderate amounts of fresh to slightly saline water.
	Comanche	Washita Fredericksburg			750	Hard, fossiliferous limestones, shale, chert, & dolomite. Some calcareous clay.	Yields little or no water.
	Comanche	Trinity	Antlers Formation: Paluxy Formation	Upper Trinity	200	Fine-grained quartz sand in part indurated by calcium carbonate cement. Locally contains thin beds of limestone and marl.	Yields very small to moderate quantities of fresh to slightly saline water.
	Comanche	Trinity	Antlers Formation: Glen Rose Formation	Upper Trinity	1,500	Alternating beds of limestone, dolomite, shale, & marl with some anhydrite & gypsum. Massive, fossiliferous limestone & dolomite in the basal part of grading upward into thin beds of limestone, shale, marl & gypsum. Corbula martinae bed at top.	
	Comanche	Trinity	Antlers Formation: Travis Peak Formation: Hensell Sand Member	Middle Trinity	175	Sand, gravel, conglomerate, sandstone, siltstone, & shale. Grades into sandy limestone & dolomite.	Yields small to large quantities of fresh to slightly saline water in the study area.
	Comanche	Trinity	Antlers Formation: Travis Peak Formation: Pearsall Member	Middle Trinity	85	Predominately shale interbedded with sand; however, in the calcareous facies, the unit is composed almost entirely of calcareous sediments.	Not known to yield water in the study area.
	Comanche	Trinity	Antlers Formation: Travis Peak Formation: Cow Creek Limestone Member	Middle Trinity	130	Massive, often sandy, dolomitic limestone, frequently forming cliffs and waterfalls. Contains gypsum & anhydrite beds.	
	Comanche	Trinity	Antlers Formation: Travis Peak Formation: Hammett Shale Member	Middle Trinity	140	Shale & clay with some sand, dolomitic limestone & conglomerate.	
	Comanche	Trinity	Antlers Formation: Travis Peak Formation: Sligo Member	Lower Trinity	130	Limestone, dolomite, occasionally sandy, & shale. Thins to the west.	Yields moderate to large quantities of fresh to moderately saline water.
	Comanche	Trinity	Antlers Formation: Travis Peak Formation: Hosston Member (Sycamore Sand in outcrop)	Lower Trinity	1,550	Basal conglomerate grading upward into a mixture of sand, siltstone, & shale, with some limestone beds.	
Pre-cretaceous						Conglomerate, sandstone, & shale, siltstone, & some limestone.	Locally yields small amounts of usuable water.

* *Yeild, 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.*

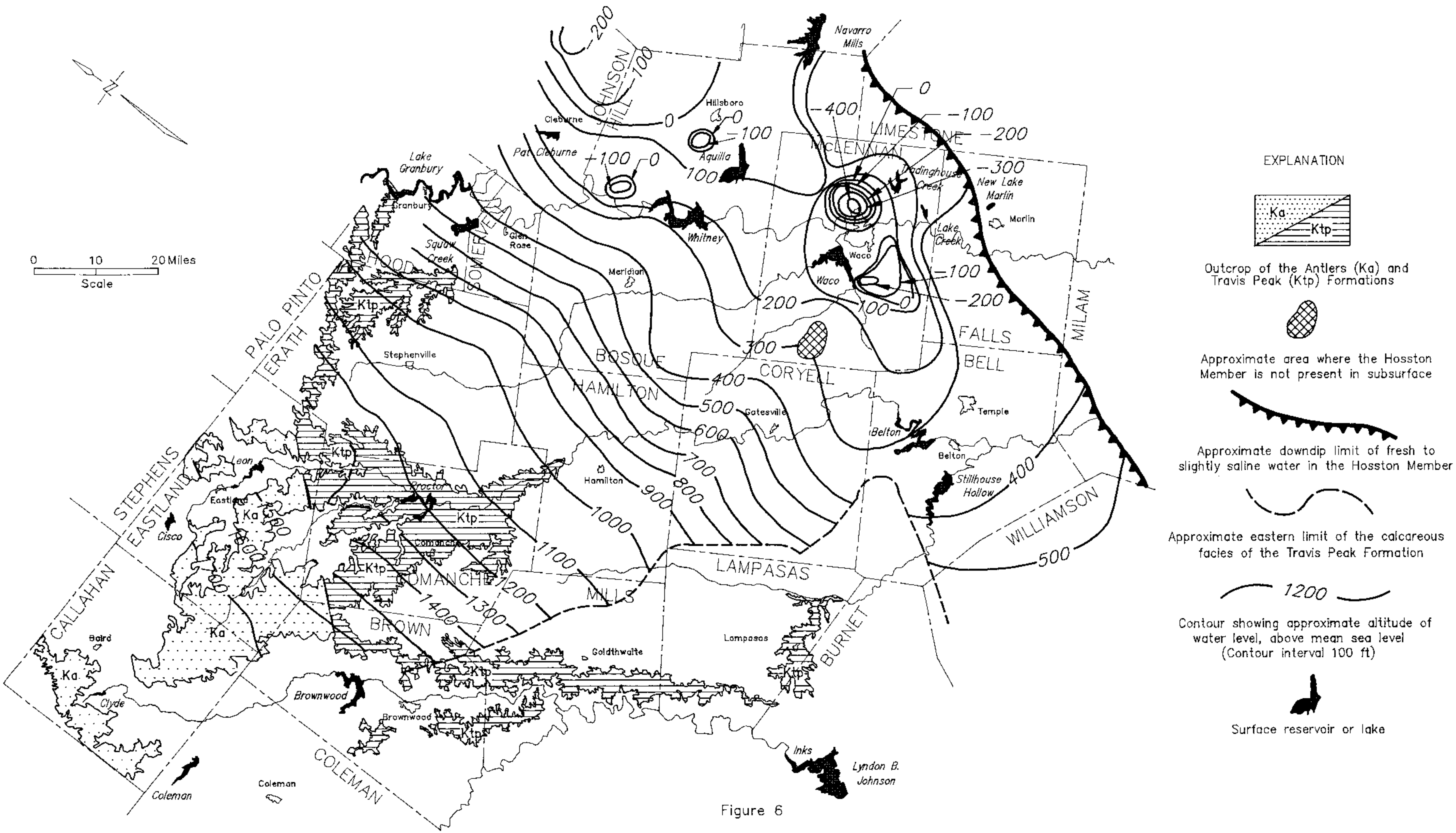


Figure 6

APPROXIMATE ALTITUDE OF WATER LEVELS IN THE ANTLERS AND TRAVIS PEAK FORMATIONS, AND THE HOSSTON MEMBER, TRINITY GROUP, SPRING 1988

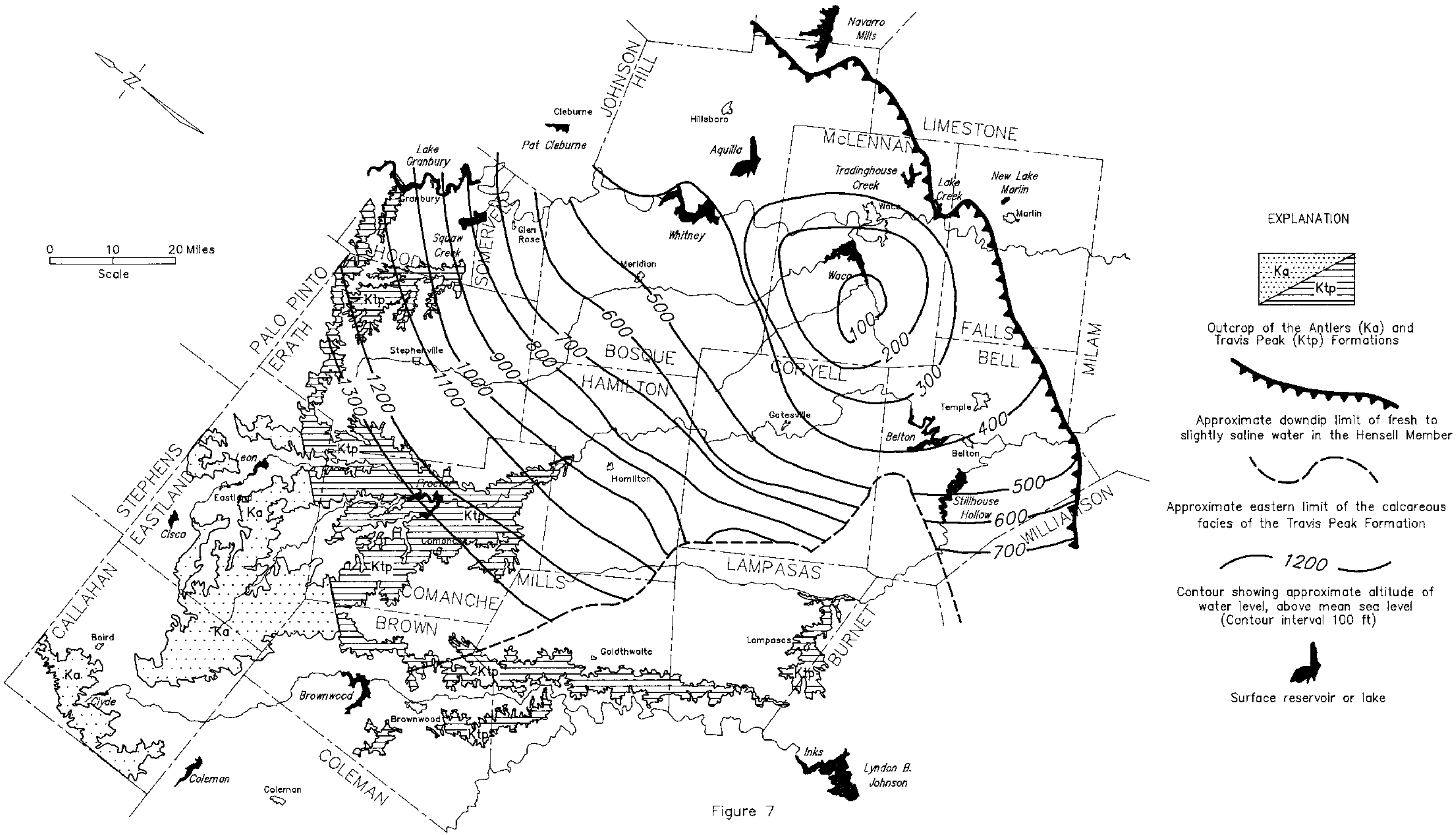


Figure 7

APPROXIMATE ALTITUDE OF WATER LEVELS IN THE HENSELL MEMBER OF THE TRAVIS PEAK FORMATION, TRINITY GROUP, SPRING 1988

Water in an aquifer is under either water-table or artesian conditions. In the outcrop area, ground water generally occurs under water-table, or unconfined conditions; it is under atmospheric pressure only, and the water table will rise or fall in response to changes in the volume of water stored. The hydraulic gradient in an unconfined aquifer coincides with the slope of the water table which corresponds to the general slope of the land surface.

Downdip from the outcrop or recharge area, ground water within an aquifer occurs under artesian or confined conditions as a result of being overlain by relatively impermeable beds which confine the water under pressure greater than atmospheric. In a well penetrating an artesian aquifer, water will rise above the confining bed and, if the pressure head is large enough to cause the water in the well to rise above the land surface, the well will flow. The level or surface to which water will rise in an artesian well is called the piezometric surface. The hydraulic gradient of an artesian aquifer is the slope of the piezometric surface.

Recharge, Movement, and Discharge

Recharge is the process by which water is added to an aquifer. Precipitation on the outcrop of an aquifer is generally the most significant natural source of recharge; however, water may enter from surface streams and lakes on the outcrop and possibly through interformational leakage. Artificial recharge may be accomplished by injection wells, infiltration of irrigation water, or water spreading on the outcrop. The amount of recharge must balance the discharge over a long period of time or the water in the aquifer will eventually be depleted. Factors which influence the amount of recharge received by an aquifer in its outcrop area are the amount and frequency of precipitation, rate of evaporation, types and condition of soil cover, topography, type and amount of vegetation, and the extent of the outcrop area. In addition, the ability of the aquifer to accept recharge and transmit it to areas of discharge influences the amount of recharge it will eventually receive. Recharge is generally greater during winter months when plant growth, pumpage, and evaporation rates are all low.

Ground water moves in response to the hydraulic gradient from areas of recharge to areas of discharge. Ground water under artesian conditions generally moves in the direction of the aquifer's regional dip, while movement of ground water under water-table conditions is generally toward the surface drainage system. In areas of large and extensive withdrawals by wells, the natural gradient is altered and ground water moves from all directions toward the areas of pumpage or lowered pressure. The rate of movement of ground water is directly related to the porosity and permeability of the aquifer. In most sands and gravels, the rate of movement may be on the order of a few tenths of a foot per day or many feet per year, while in cavernous gypsum or limestone, water flows in subterranean channels and may have velocities and volumes comparable to surface streams.

Discharge is the process by which water is removed from an aquifer. Natural discharge includes springs, effluent seepage to streams, lakes, and marshes which intersect the water table, transpiration through vegetation, evaporation through the soil where the water table is close to the land surface, and interformational leakage as a result of differences in head. Ground water is artificially discharged from flowing and pumped water wells, and by drainage ditches, gravel pits, and other forms of excavation that intersect the water table.

Hydraulic Characteristics

The quantity of water an aquifer yields depends upon its ability to store and transmit 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 relationships between well yield and the coefficients of permeability, transmissibility, and storage.

The most permeable sands in the Trinity Group aquifer occur in the outcrop areas within Brown, Callahan, Comanche, Eastland, and Erath Counties. Permeability coefficients range from approximately 87 to 235 gallons per day per square foot (gpd/ft^2) (Klemt et al. 1975). Because of the extreme range in permeability in water-saturated sands, transmissibility values vary widely, ranging from zero to 20,000 gpd/ft (Klemt et al. 1975).

The sands within the calcareous facies of the Trinity Group aquifer have extremely low permeabilities due to cementation and range from 1 to 20 gpd/ft^2, with coefficients of transmissibility ranging from zero to 1,000 gpd/ft (Klemt et al. 1975)

Elsewhere in the study area, the downdip artesian portion of the Hosston Member of the Travis Peak Formation has coefficients of permeability ranging from approximately 17 to 171 gpd/ft^2 (Klemt et al. 1975). Transmissibility values vary widely, ranging from 2,700 to 4,200 gpd/ft . Storage, a dimensionless value, ranges from 0.000028 to 0.000077 (Klemt et al. 1975).

The artesian portion of the Hensell Member has coefficients of permeability ranging from 26 to 126 gpd/ft^2 (Klemt et al. 1975). The Hensell thins and becomes shaley downdip; correspondingly, a range in coefficients of transmissibility can be expected from zero to 15,000 gpd/ft (Klemt et al. 1975). Test data was not available in the study area to assign a coefficient of storage range to the Hensell.

Water Quality

The chemical character of water mirrors the mineral composition of the rocks through which it has passed. As water moves through its environment, its solvent power 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 water is in contact with the rock, and the concentration of carbon dioxide present within the water. Additionally, dissolved mineral concentrations generally increase with depth and temperature (Nordstrom, 1987). Neutralizing or removing the unwanted constituents is usually difficult and can be very costly.

Standards for specific mineral constituents are thoroughly discussed in Texas Water Development Board Reports 195 and 298. These standards vary according to the type of water usage.

Chemical analyses of 269 water samples collected by Texas Water Development Board staff provided the generalizations used for this study. These samples were obtained over the past five years, with several checked for content of heavy metals (arsenic, barium, cadmium, chromium, copper, iron, lead, manganese, mercury, selenium, silver, and zinc) and for radioactivity.

Ground water pumped from the predominantly water-table conditions associated with the outcrop of the Travis Peak, Antlers, and Paluxy generally meets all Texas Department of Health primary and secondary standards for public water supply. These include the heavy metals and radioactivity standards already mentioned; only nitrate consistently reflected elevated levels. The domination of calcium and bicarbonate in this water gives it an average total hardness of 430 milligrams per liter (mg/l), considered to be a very hard water.

Most of the water wells in the central portion of the study area are completed in the Hensell Member, which is preferred over the Hosston because of the shallower depths and cheaper drilling costs.

The mean total dissolved solids (TDS) content of water from wells completed in the Hensell is approximately 955 mg/l. This is near the Texas Department of Heath recommended limit of 1,000 mg/l. About 33 percent of the sampled wells exceed this limit. Hensell wells usually have high concentrations of sodium. The aquifer is classified as a sodium-bicarbonate type. Iron and sulfate content are usually very close to the recommended Texas Department of Health standards. About 29 percent of the sampled wells exceed the sulfate standard. Over 41 percent of the sampled wells exceed the recommended limit for fluoride.

The majority of the population using ground water in counties located along Interstate Highway 35 use water from wells completed in the Hosston Member of the Travis Peak Formation because of the poor quality water from the overlying Hensell Sand Member.

The Hosston has a sodium chloride type water in the study area, with an average concentration of 335 mg/l of sodium in sampled wells. Ground water sampled from the Hosston has a mean temperature of about 34°C (93.2°F). The mean total dissolved-solid content was 915 mg/l from selected wells completed in the Hosston with only about 18 percent of the samples exceeding this mean. The ground water is also classified as a "soft" type water with a hardness content of usually under 45 mg/l. Although mean fluoride is reported as 1.3 mg/l, over 40 percent of the samples analyzed exceeded this average. Wells completed near the downdip limit of usable quality water (3,000 mg/l) in the Hosston have high iron concentrations. About 50 percent of the water from wells analyzed exceeded the recommended pH limit of 8.5. The majority of wells completed in the Hosston east of Interstate Highway 35 produced ground water having chemical constituents exceeding recommended Texas Department of Health standards.

Only a limited number of wells were sampled in the Paluxy Formation and Woodbine Group because of the small surface exposures and deterioration of ground water within a short distance downdip. The wells sampled from the Paluxy had a mean of 842 mg/l total dissolved-solids. The ground water from the Paluxy exceeds the recommended fluoride limits and is moderately hard with a value of 116 mg/l of calcium carbonate ($CaCO_3$).

Wells completed in the Woodbine yield good quality water at or very near the outcrop. However the residual sodium carbonate (RSC) and percent sodium generally limit its use for irrigation, while high iron and fluoride content restricts it use for public supply.

Wells developed in the Brazos River alluvium provide small to large amounts of fresh to moderately saline water in much of the central study area along the Brazos River. These wells are predominately used for irrigation.

None of the wells sampled within the study area showed excessive amounts of heavy metals or radioactivity (alpha or beta, nor Radium 226 or 228).

GROUND-WATER PROBLEMS

Water-Level Declines

A serious problem associated with the withdrawal of ground water from the Trinity Group aquifer is the decline of artesian pressure (water levels) throughout a large part of the study area.

Fluctuations of water levels can be caused by several factors. However, the primary cause is a change in the amount of water in storage. Seasonal fluctuations are the result of changes in the amount of precipitation and evapotranspiration at the aquifer's recharge zone. In general, the amount of recharge versus discharge in an aquifer controls the water level. When recharge exceeds discharge, then levels rise, and when discharge exceeds recharge the result is a decline in the water level or, under artesian conditions, a lowering of the hydrostatic head. Figures 8, 9, and 10 illustrate water-level fluctuations for aquifers in the study area.

On or near the outcrop, the aquifer is unconfined and water-table conditions exist. Historical information indicates that water levels in and near the outcrop fluctuate seasonally in response to the amount of rainfall and pumpage. Although about 50 percent of the pumpage from the Trinity Group aquifer occurs in the outcrop area, no long-term declines have developed. The lack of a long-term decline may be attributed to the good recharge conditions that exist in the outcrop and the large percentage of the amount of water pumped for irrigation which is returned to the aquifer. Hydrograph of well 31-55-114 (Erath County) shown on Figure 8 illustrates the historical water-level fluctuations typical of the outcrop area.

The 1988 altitude of water levels in wells completed in the Antlers and Travis Peak Formations and Hosston Member are shown in Figure 6. A regional cone of depression exists in McLennan County centered in the Waco area. Two smaller cones are present within the regional cone. One cone is centered barely north of Waco at the Town of Lacy-Lakeview and the other south-southwest of Waco at the City of Woodway and surrounding the communities of Hewitt and Robinson.

Total cumulative water-level declines in the these same Trinity Group strata for a 21-year period from 1967-88 are shown on Figure 11. Approximately 60 percent of the study area has experienced some water-level declines during this period, and about 40 percent of the area has experienced declines of 100 feet (4.8 ft/yr) or more. Additionally, declines greater than 200 feet (9.5 ft/yr) have occurred during this period in portions of Bell, Bosque, Falls, Hill, and McLennan Counties. Declines in excess of 300 feet (14.3 ft/yr) are present in the Itasca-Hillsboro area in Hill County, near the community of Axtel in McLennan County, and in the Valley Mills-China Springs area in southeastern Bosque and northwestern McLennan Counties. Declines greater than 400 feet (19.0 ft/yr) have occurred southwest of Waco in the vicinity of Woodway. Hydrographs shown on Figure 8 illustrate the water-level changes in three wells completed in the Hosston Member.

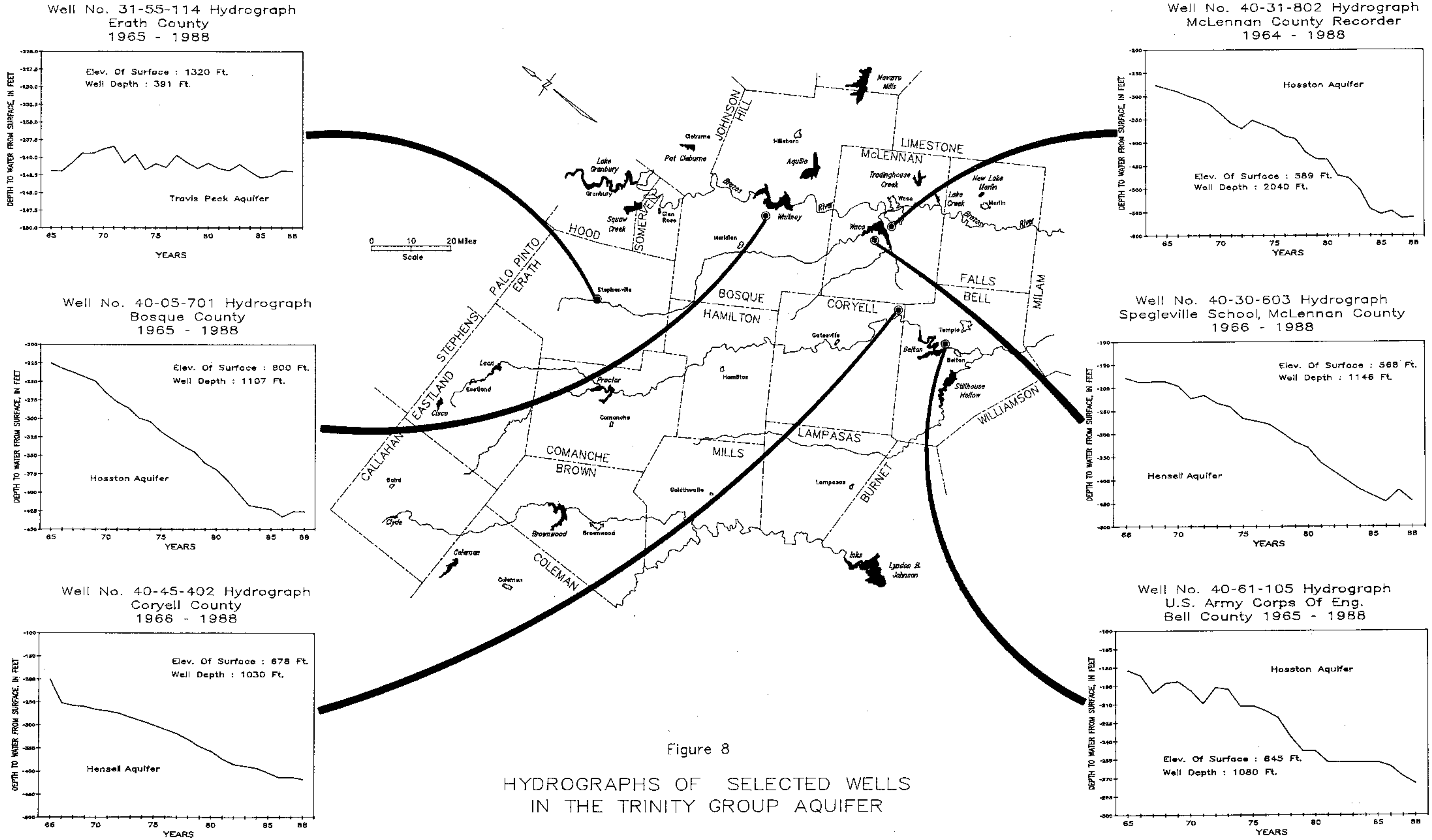


Figure 8

HYDROGRAPHS OF SELECTED WELLS IN THE TRINITY GROUP AQUIFER

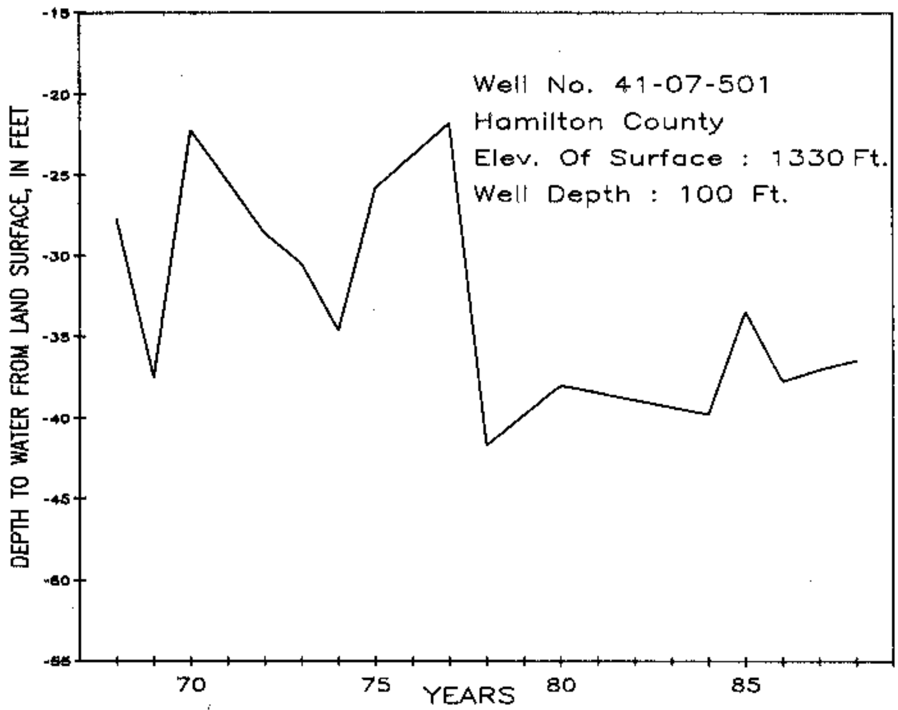


Figure 9

HYDROGRAPH OF A WELL IN THE PALUXY AQUIFER

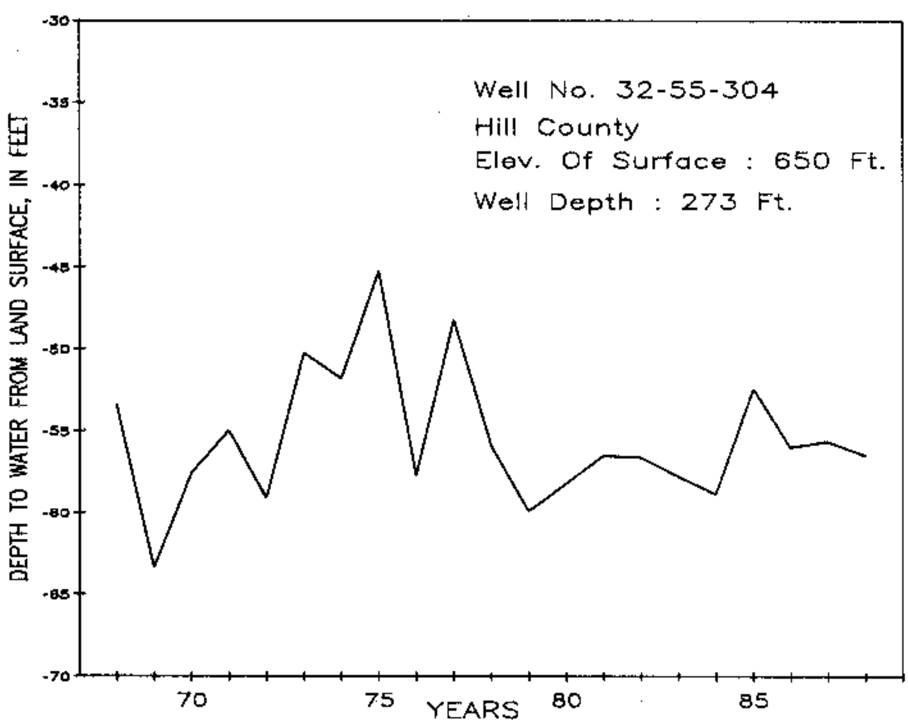


Figure 10

HYDROGRAPH OF A WELL IN THE WOODBINE AQUIFER

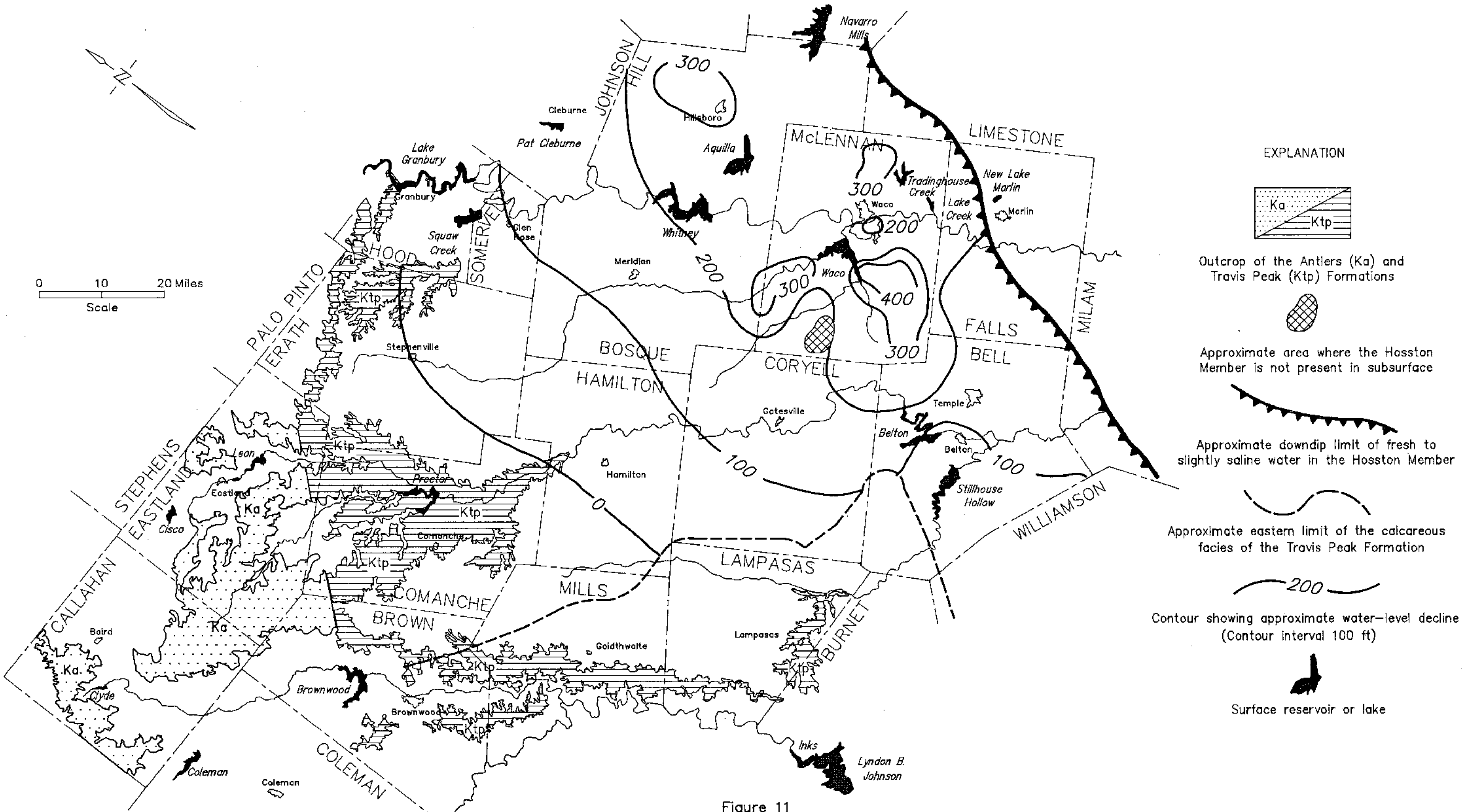


Figure 11

WATER–LEVEL DECLINES IN THE ANTLERS AND TRAVIS PEAK FORMATIONS, AND THE HOSSTON MEMBER, TRINITY GROUP, 1967–1988

Water-level declines shown on Figure 12 have occurred in these strata during an 8-year period from 1980 through 1988. Twenty five percent of the area has experienced water-level declines of 50 feet or more (6.2 ft/yr). Water-level declines of more than 100 feet (12.5 ft/yr) have occurred throughout much of McLennan and Hill Counties and declines of up to 400 feet (50.0 ft/yr) have been recorded in a limited area southwest of Waco in the vicinity of Woodway.

During the period 1967-88, average water-level declines ranged from zero to more than 19 feet per year. Average declines of 5 to more than 14 feet per year were common throughout most of McLennan, Hill, and parts of Bell, Bosque, and Coryell Counties. However, more recent (1980-1988) declines have ranged from zero to more than 50 feet per year with average annual declines of 12 to 37 feet per year common in McLennan and Hill Counties. Comparing Figures 11 and 12 indicates that historically only moderate declines averaging about 12 feet per year since 1967 have occurred in the Lacy-Lakeview area. In the past eight years a significant increase in the average rate of decline has occurred in this area. This comparison also indicates that the large decline in the Woodway area (McLennan County) has occurred primarily in the past eight years at a rate of decline of over 50 feet per year.

For the Hensell Member of the Trinity Group aquifer, current (1988) water levels of wells are shown in Figure 7. A broad cone of depression extends across western McLennan County with the center west of Waco near the community of China Springs.

The cumulative decline in water-levels in the Hensell Member for the 21-year period from 1967-88 is shown on Figure 13. Water levels in the Hensell Member have declined over an area as extensive as the Hosston Member, but not of the same magnitude in rate of decline. Declines of 100 feet (4.89 ft/yr) or more have occurred in about 35 percent of the study area. In the center of the cone of depression, water-level declines are in excess of 250 feet (12.0 ft/yr).

Figure 14 shows the water-level changes of the Hensell Member from 1980-88. This illustration shows a more focused cone of depression with a steeper gradient. The magnitude of declines toward the center of the cone are greater than 200 feet (25 ft/yr), indicating that 80 percent of the decline has occurred in the past eight years. Hydrographs of wells 40-45-402 (Coryell County) and 40-30-603 (McLennan County) in Figure 8 illustrate the declines in water levels in these wells completed in the Hensell Member.

The financial impact of continuing water-level declines can include an increase in pumping cost, the cost of lowering pumps, decreased well yields. Pump settings and subsequent lifts in wells outside of the regional cone of depression range from 250 feet below land surface in Hamilton and Erath Counties to 900 feet in Coryell and Bosque Counties. Within the cone of depression in the Waco-Hillsboro-Temple area pump settings range from about 800 feet to 1400 feet below land surface. The higher pumping lifts cause increased operating expenses which result in higher water costs.

Water-level declines, reflecting reduced hydrostatic pressure, may have an adverse effect on the natural quality of water in the aquifers by causing encroachment and interformational leakage of poorer quality water.

Water Quality

Several existing and potential water-quality problems exist in the study area. Contamination of ground water in the outcrop occurs from two apparent sources, oil-field brines and organic material.

Brines, waters containing more than 35,000 mg/l of total dissolved solids, are a by-product of oil and gas operations. Brine disposal has produced vegetative kills in several areas where it was allowed to flow onto the ground (Nordstrom, 1987). Because of the sandy nature of soil on the outcrop, brines can readily percolate downward to contaminate the ground water. The resulting increase in content of dissolved solids as shown in Figure 15 can make the water unsuitable for drinking and irrigation. Poorly plugged oil or gas wells sometimes allow poor quality water to encroach upon fresh-water sands. Nordstrom (1987) has defined several of these areas and they are included on Figure 16.

High bacterial counts and high nitrate concentrations are associated with organic contamination. A nitrate (as NO_3) concentration in excess of 44.3 mg/l has been known to cause "blue baby" disease. In shallow wells, organic contamination often occurs where surface water is allowed to enter the well annulus. However, proper casing and cementing methods during well construction can usually prevent this type of contamination (Nordstrom, 1987). Though still within Texas Department of Health recommended limits, several wells in Callahan, Eastland, Erath, Brown, and Comanche Counties have unusually high nitrate contents. Particular concern is centered within an area in northern Comanche and southeastern Eastland Counties (Figure 16) where sampled wells have recently been exceeding the standard nitrate limits of 44.3 mg/l (Figure 15). Additional, unsubstantiated reports have nitrate contamination associated with a growing dairy industry in Erath County. The Texas Department of Agriculture, Texas Water Development Board, and Texas A&M University are investigating these reports.

Barium is a naturally occurring element, large concentrations of which can have toxic effects. Several wells sampled from the Antlers and Travis Peak Formations have exhibited elevated barium readings though they are still within Texas Department of Health limits. These higher readings may represent a long-term accumulation from oil and gas exploration as barium is widely used in drilling muds.

Where the Glen Rose Formation is at the surface, its recharge contributes to the underlying Travis Peak Formation or the Hensell Member of the Trinity Group because there is no aquitard between the formations (Rapp, 1988). Water from the Glen Rose is usually higher in sodium, chloride, and sulfate content and any interformational leakage could alter and adversely affect the overall chemical quality of ground water in the underlying units. The leakage is enhanced where poor well completion techniques are combined with heavy withdrawal (pumpage), thereby allowing hydrostatic displacements that encourage interformational communication. When this occurs, the sulfate-rich Glen Rose waters enter and mix with the native formational waters below. This is less likely to occur in the Hosston Member, where the overlying Hammett Shale acts as an aquitard to prevent leakage from occurring.

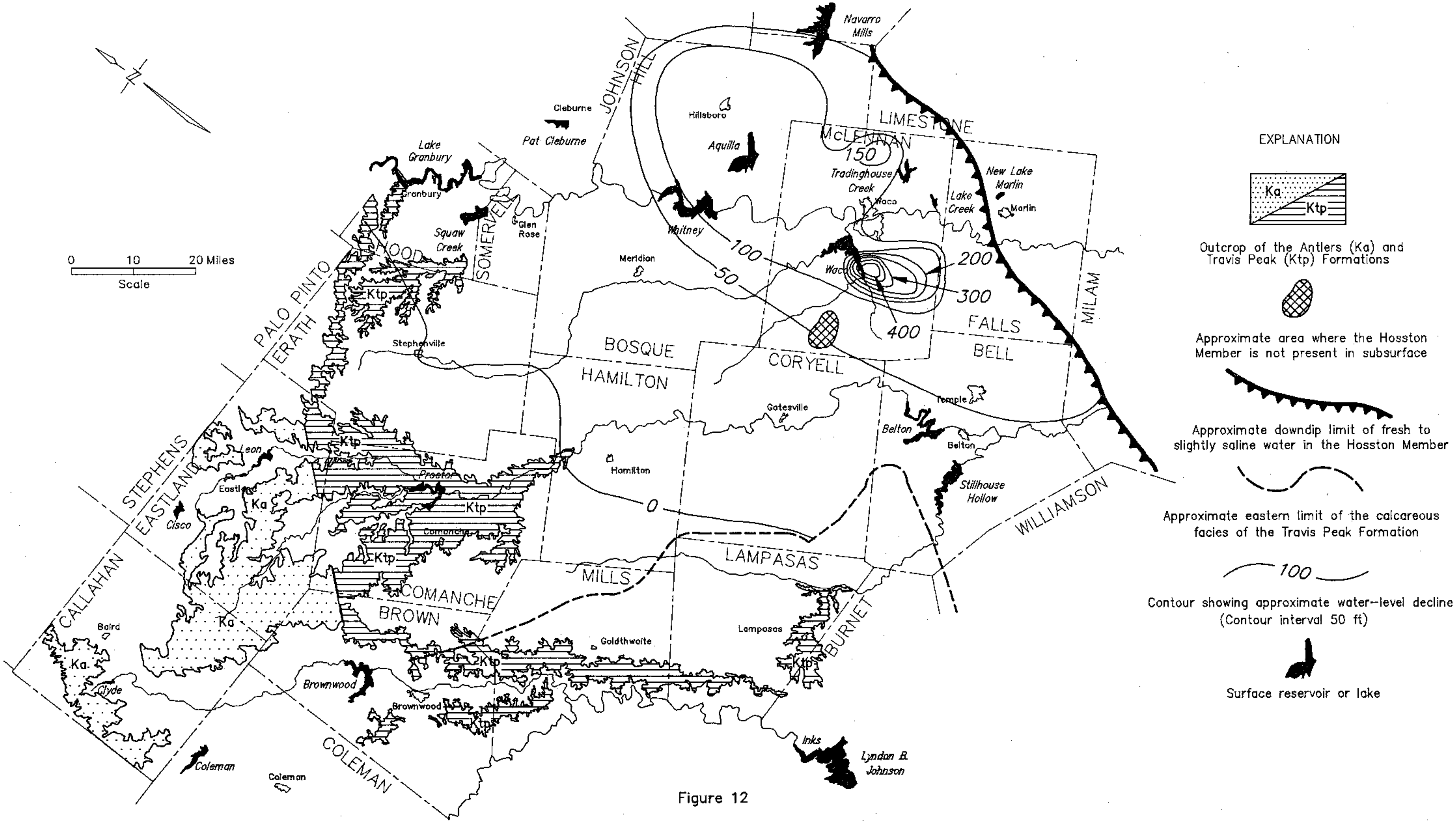


Figure 12

WATER-LEVEL DECLINES IN THE ANTLERS AND TRAVIS PEAK FORMATIONS, AND THE HOSSTON MEMBER, TRINITY GROUP, 1980–1988

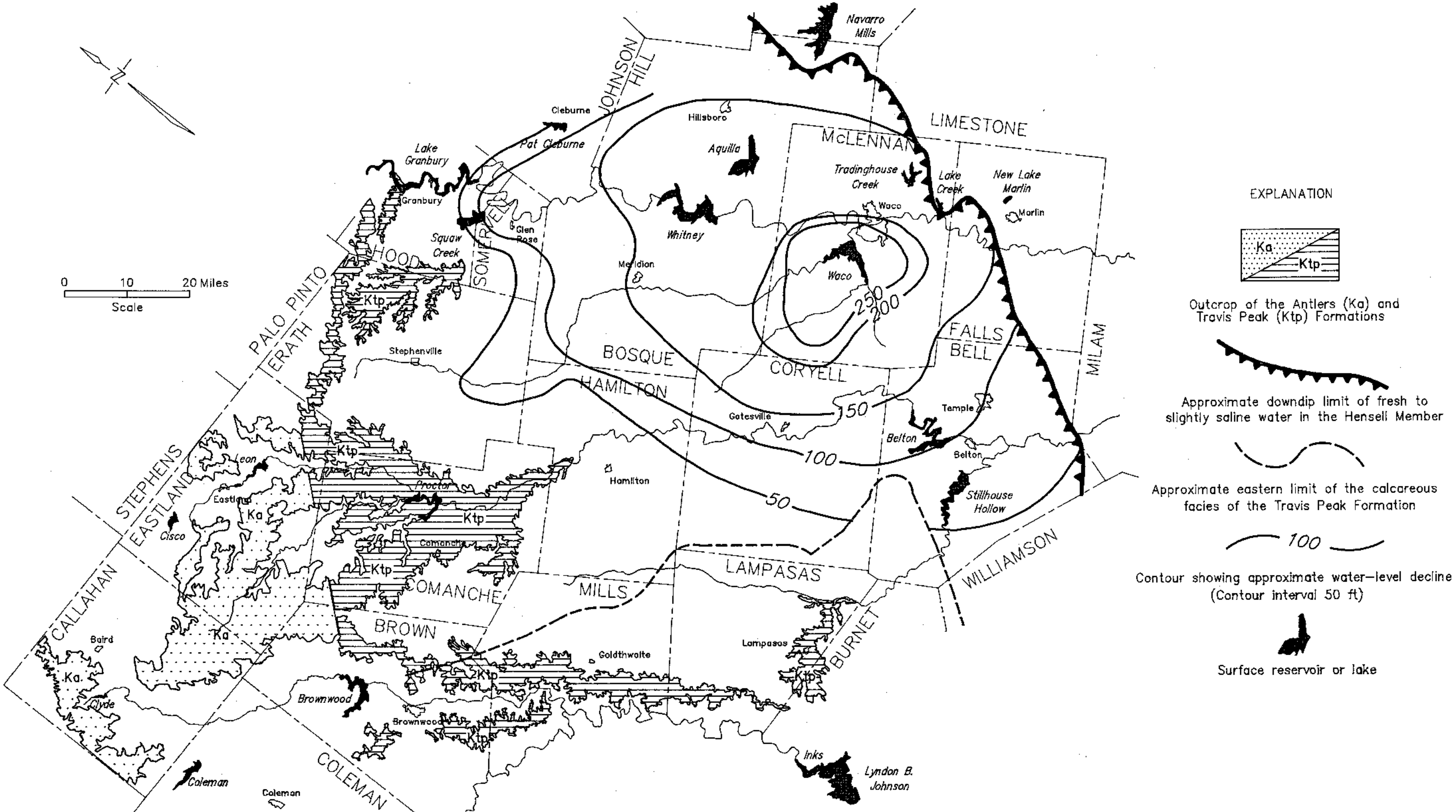


Figure 13

WATER-LEVEL DECLINES IN THE HENSELL MEMBER OF THE TRAVIS PEAK FORMATION, TRINITY GROUP, 1967-1988

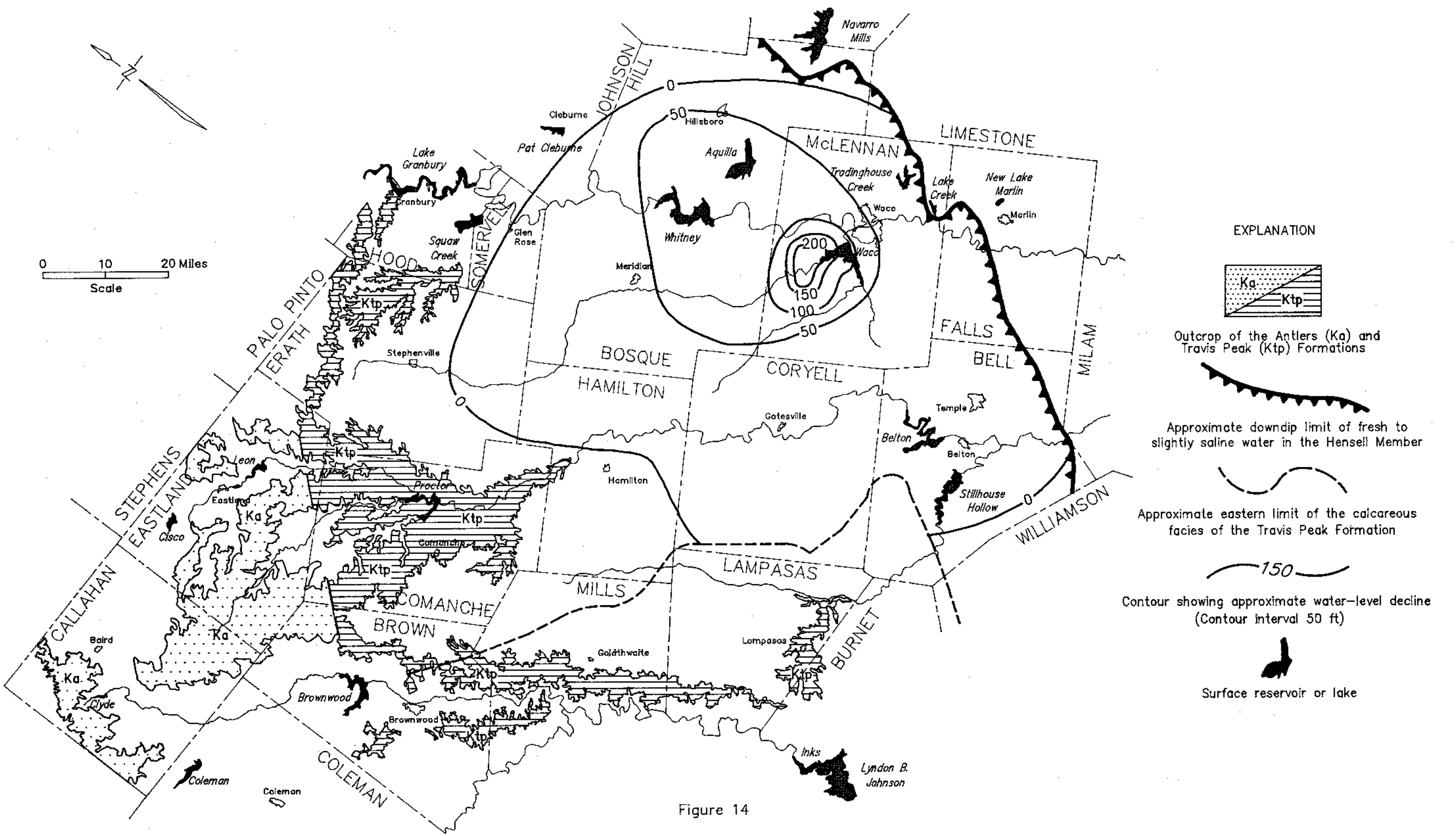
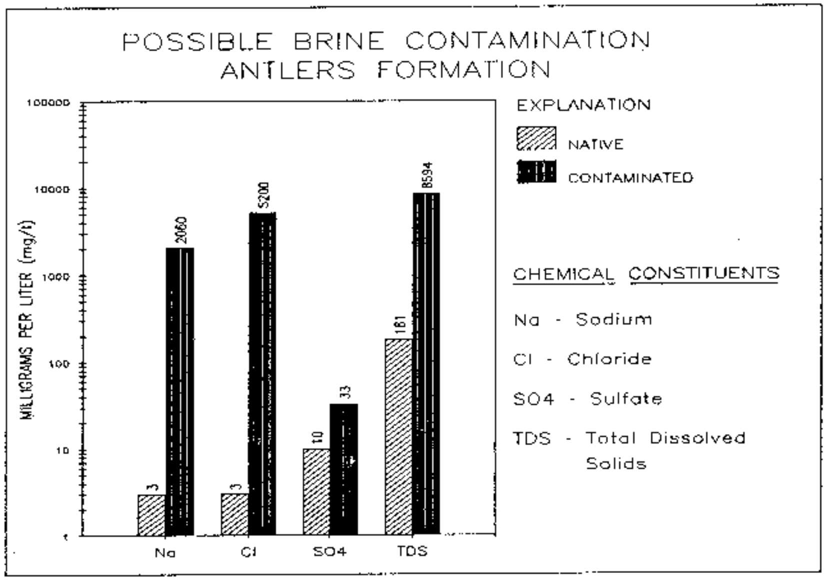
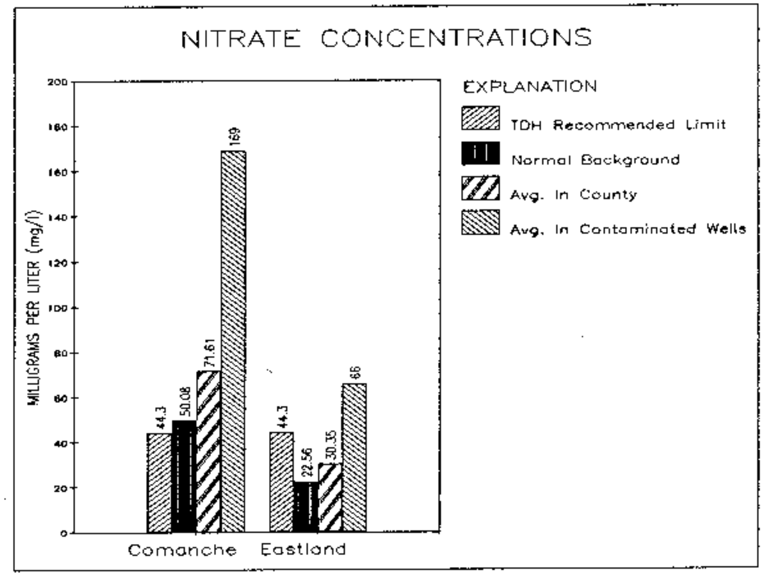


Figure 14

WATER-LEVEL DECLINES IN THE HENSELL MEMBER OF THE TRAVIS PEAK FORMATION, TRINITY GROUP, 1980--1988





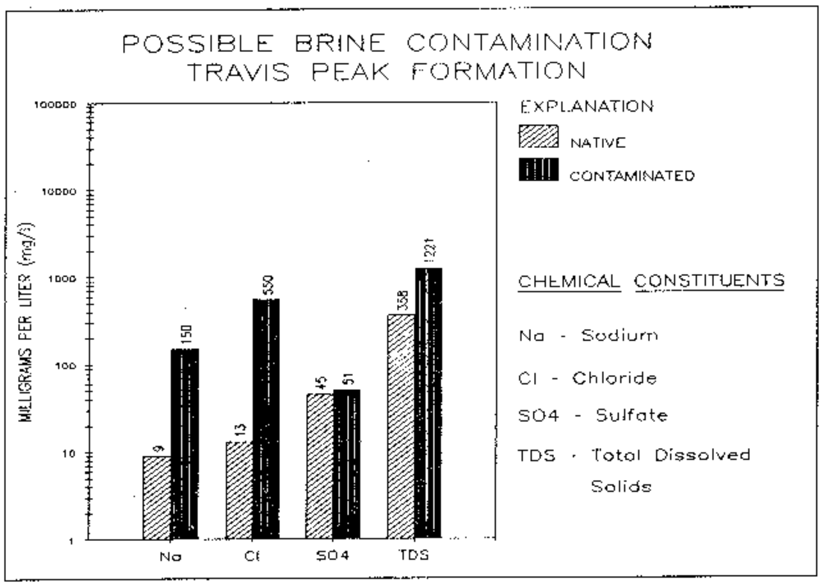


Figure 15

EXAMPLES OF WATER QUALITY PROBLEMS ASSOCIATED WITH THE OUTCROPS OF THE ANTLERS AND TRAVIS PEAK FORMATIONS

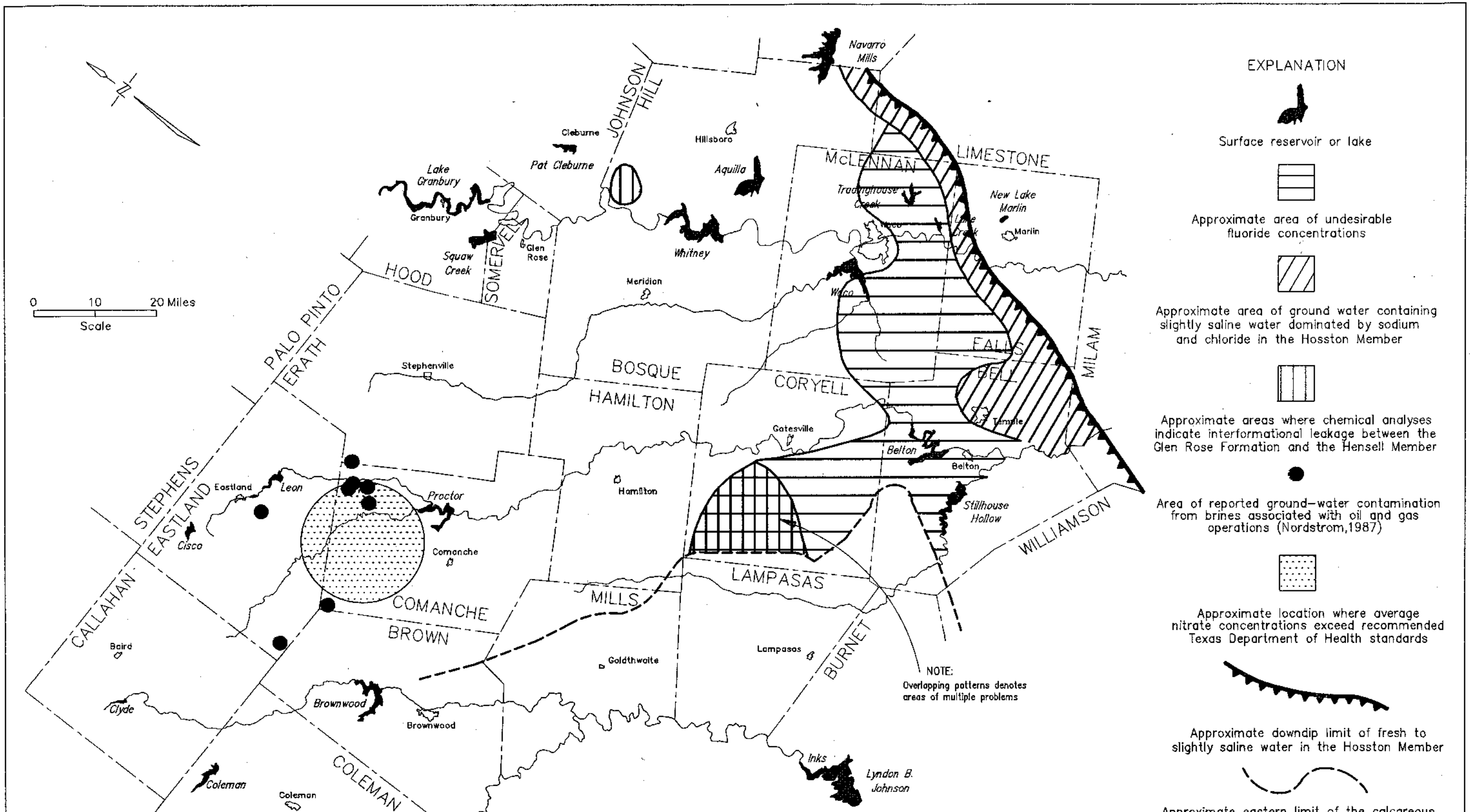


Figure 16

AREAS WITH SIGNIFICANT WATER-QUALITY PROBLEMS

Several wells in western Coryell County are completed in the Hensell Member and exhibit the sodium-sulfate type ground water that is believed to be the result of leakage from the Glen Rose (Figure 16). Sulfate, fluoride, chloride, and total dissolved-solids contents in these wells commonly exceed Texas Department of Health recommended limits.

An apparent example of induced interformational leakage is present in a well in northwestern Hill County at the City of Blum. Water level gradients in Figures 6, 7, 12, and 14 indicate an area of heavy pumpage at Blum with a decline rate of 7 feet per year over the last 24 years, with much of the decline occurring in the last 10 years at an annual rate of about 10 feet per year. Over a 26- year period at Blum, the dissolved-solids content of produced Hensell water has increased from 485 to 1,528 mg/l. In 1980 the overall dissolved-solids content of the ground water was 910 mg/l, but in 1986 it had deteriorated to 1,528 mg/l. The increase in total dissolved solids corresponds to water-level declines at Blum. The dominate water type has undergone a geochemical facies change from a sodium-bicarbonate to a sodium-sulfate-bicarbonate and finally to the present sodium-sulfate water (Figure 17). This change is indicative of interformational leakage between the overlying Glen Rose Formation and the Hensell Member of the Trinity Group aquifer. This well now exceeds the Texas Department of Health's recommended standards for dissolved-solids, fluoride, and sulfate contents. The City of Blum is currently in the process of determining the most economical solution to this problem.

Additionally, large and continuing water-level declines have reversed the natural water-level gradient near the downdip (eastern) side of the study region and have developed an elongated trough in the piezometric surface (Figure 6). Mineral concentrations in this trough may, in time, become more pronounced due to the induced reversal of ground-water flow. Under pre-pumpage conditions, water migrated eastward to regions of greater depth and temperature near the Balcones Fault Zone, leading to rapid increases in salinity eastward (Rapp, 1988). Figure 18 illustrates the effect of depth on temperature of water in the Hosston Member. As a result of the piezometric trough, a potential exists for water of elevated salinity to migrate back updip toward the centers of pumpage. This study did not develop conclusive evidence of water-quality deterioration along the downdip limit of slightly saline water (3,000 mg/l). However, the potential for the updip movement of poor quality water exists and is likely to become more acute as water levels continue to decline.

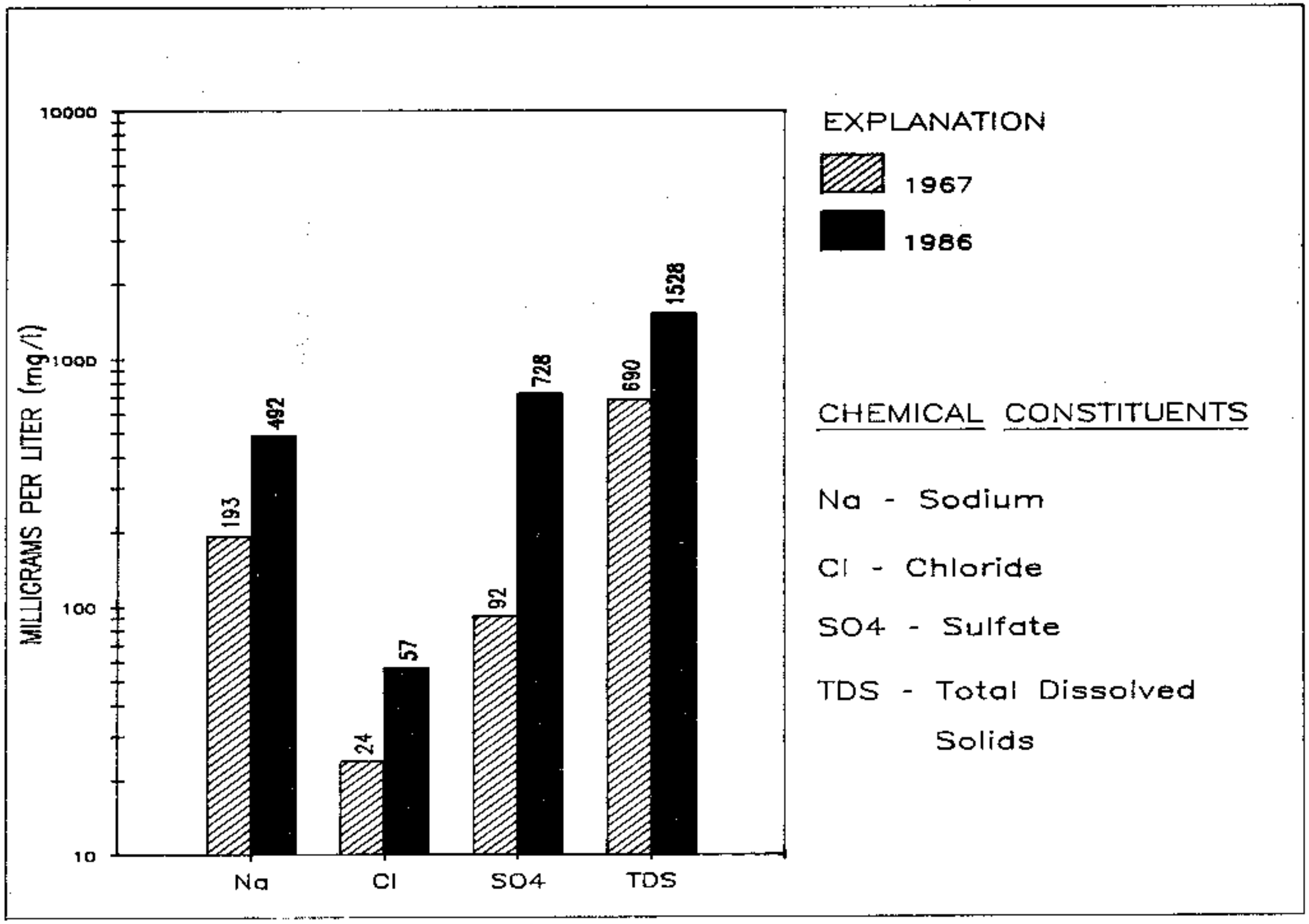


Figure 17

COMPARISON OF SELECTED CHEMICAL CONSTITUENTS IN THE HENSELL MEMBER, CITY OF BLUM, HILL COUNTY, 1967 AND 1986

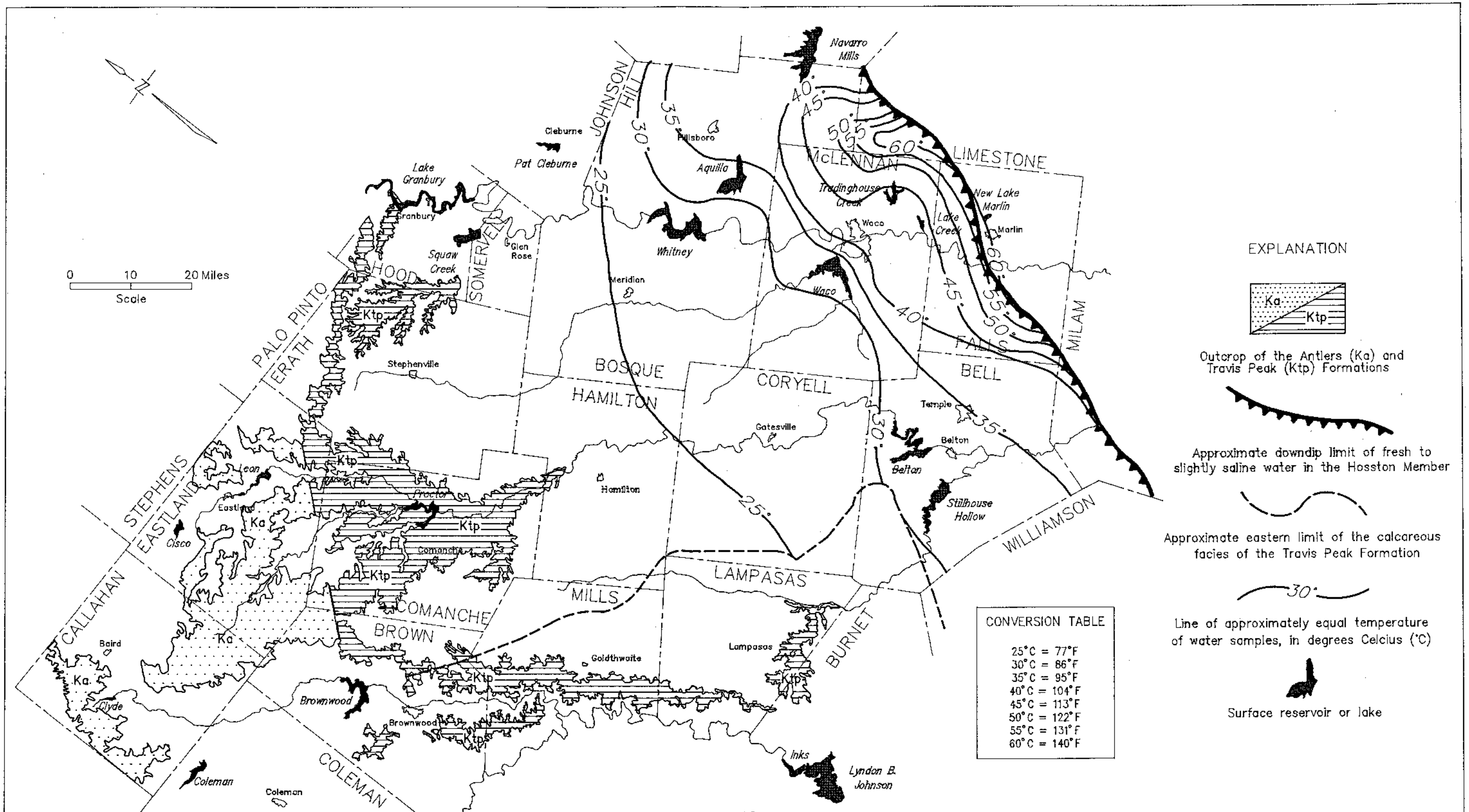


Figure 18

APPROXIMATE TEMPERATURE OF WATER FROM THE HOSSTON MEMBER OF THE TRAVIS PEAK FORMATION

WATER DEMANDS

Population

The 1980 and 1985 populations 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. Department of Commerce, Bureau of the Census. The population of cities with over 1,000 people were taken from Bureau of Census statistics. Rural areas and cities with less than 1,000 population are considered collectively as "County Other". 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 produced by projecting previously calculated growth rates to 1990 and interpolating for 1985. Population projections were estimated by extending Bureau of Census Statistics according to growth rates used in the 1988 Texas Water Development Board Revised Data Series.

The population of the study area increased 8 percent during the period 1980 to 1985. The projected population of the study area is forecast to increase by 30 percent from 1980 to the year 2000, and by 48 percent from 1980 to 2010. The highest projected growth for a major city within the study area is at Hewitt with a 197 percent increase from 1980 to 2010. The highest projected growth in a county occurs in Lampasas County, with a 166 percent increase by 2010. The least amount of projected growth, only 1 percent, occurs in Hamilton County.

Water Use

Since the early 1900's, the Antlers and Travis Peak Formations have been developed to provide large amounts of ground water for public supply, industrial, irrigation, domestic, and livestock needs.

In 1967, a little over 42,000 acre-feet of ground water was pumped from the Antlers and Travis Peak Formations (Klemt, et al., 1975). In 1985 a total of 80,930 acre-feet of ground water was pumped from all aquifers within the study area with 76,884 acre-feet (95 percent) pumped from the Trinity Group aquifer (Texas Water Development Board, 1988). The following table shows the pumpage from all aquifers by use for 1985.

Use	1985 Pumpage (acre-feet)
Public supply	13,486
Irrigation	45,242
Industrial	4,202
Domestic	13,428
Livestock	4,572
Total	80,930

Water Development Board (1988)
Revised Data Series

Table 2

Current and Projected Population in the Study Area [1]

	1980	1985	1990	2000	2010
Major Cities [2]	376,550	410,426	434,311	487,034	552,993
County Other [3]	121,829	126,195	139,691	159,993	183,675
Total	498,379	536,621	574,002	647,027	736,668

	1980	1985	1990	2000	2010
*Bell	148,522	163,585	174,642	209,680	250,665
Bosque	13,401	14,211	15,217	17,590	19,567
*Brown	2,334	2,643	2,739	3,547	4,461
*Burnet	0	0	0	0	0
*Callahan	1,729	1,762	1,828	2,001	2,558
*Comanche	12,482	12,747	12,945	13,576	14,783
Coryell	56,613	56,911	59,561	70,082	85,884
*Eastland	5,136	5,409	6,149	7,037	7,818
*Erath	22,100	24,488	25,931	28,580	31,219
*Falls	8,814	9,087	9,061	10,335	10,515
Hamilton	8,297	8,088	8,078	8,277	8,397
Hill	25,284	27,891	28,992	31,288	33,240
*Lampasas	12,268	14,332	16,584	23,284	32,674
*Limestone	408	438	492	503	511
McLennan	172,006	185,455	201,315	209,250	220,811
*Milam	895	935	1,010	1,196	1,300
*Mills	3,936	3,994	4,075	4,409	4,613
Somervell	4,154	4,645	5,383	6,392	7,652
Total	498,379	536,621	574,002	674,027	736,668

1 1980 and 1985 population is based on Bureau of Census statistics. 1990, 2000, and 2010 population is based on 1988 TWDB Revised Data Series population projections.

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.

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

Public Supply

The calculated amount of ground water pumped for public supply in 1985 was approximately 13,486 acre-feet, which was a little over 17 percent of the total pumpage from the Antlers and Travis Peak Formations.

The City of Stephenville was the largest user of ground water for public supply. The city pumped a little less than 2,400 acre-feet of ground water, which was approximately 18 percent of the total amount of ground water used for public supply from the Antler and Travis Peak Formations. Stephenville obtains its supply from approximately 28 wells. These wells are completed in the Hensell and Hosston Members of the Travis Peak Formation and range in depth from 365 to 575 feet. At the present time Stephenville has a permit to obtain surface water from the proposed Paluxy Reservoir which is now in litigation.

The City of Woodway was the second largest user of ground water for public supply. The city pumped a little less than 1,500 acre-feet of ground water, which was approximately 11 percent of the total amount of ground water used for public supply from the Antlers and Travis Peak Formations. The water is pumped from six wells which range in depth from 1,800 feet to a little over 1,900 feet.

The City of Gatesville was the third largest user of ground water. The City used approximately 1,350 acre-feet of ground water, or about 10 percent of the total amount used for public supply from the Antlers and Travis Peak Formations. Since 1985 the City of Gatesville has plugged its wells and is supplied totally from surface water.

The Cities of Bellmead and Hewitt were the fourth and fifth largest users of ground water for public supply. Each city used approximately 1,100 acre-feet of ground water, which was approximately 8 percent of the total amount used for public supply. The City of Hewitt has five wells, and the City of Bellmead has four wells, all completed in the Hosston Member and ranging in depth from 1,900 to 2,400 feet.

Other towns which used a significant quantity of ground water from the Travis Peak Formation in 1985 were as follows: Robinson, about 828 acre-feet; Mart, about 591 acre-feet; Clifton, about 490 acre-feet; Glen Rose, about 404 acre-feet; West, about 402 acre-feet; Lacy-Lakeview, about 401 acre-feet; Fort Hood, about 348 acre-feet; McGregor, about 343 acre-feet; Northcrest, about 286 acre-feet; Cross Plains, about 251 acre-feet; Itasca, about 248 acre-feet; Meridian, about 242 acre-feet; and Hico, about 236 acre-feet.

Irrigation

Irrigation represents the largest category of ground-water use in the study area. In 1985 approximately 45,242 acre-feet of ground water was pumped for irrigation. This represents about 56 percent of all ground water pumped in the study area, and occurred principally in Callahan, Comanche, Eastland, and Erath Counties as shown on Figure 19. In 1985 these four counties pumped about 40,843 acre-feet which represented approximately 90 percent of the ground water used for irrigation. Comanche County alone pumped about 21,919 acre-feet for irrigation, which is about 54 percent of the ground water used in these four counties.

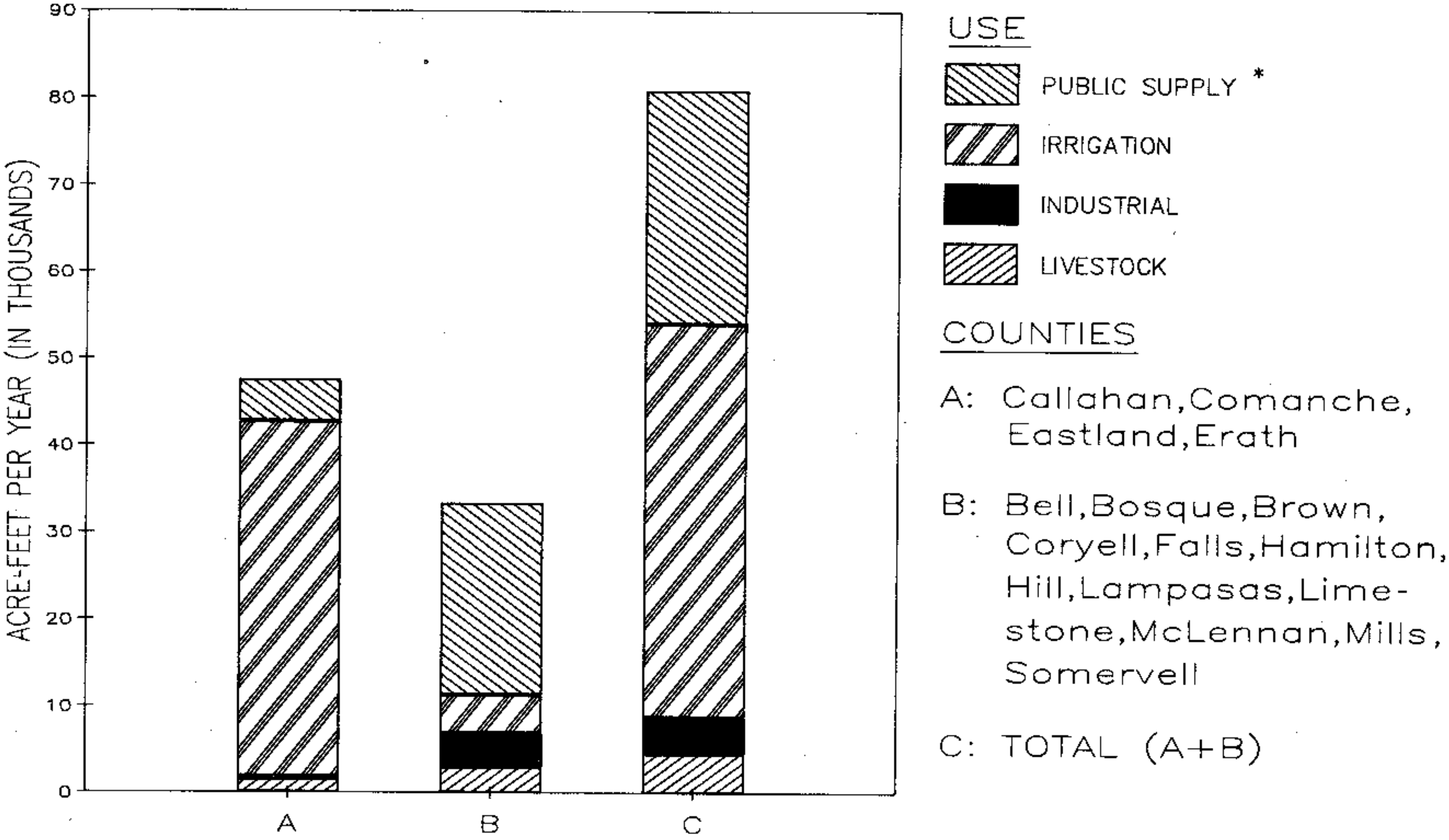


Figure 19

1985 GROUND-WATER PUMPAGE, BY TYPE OF USE

* Includes Municipal And Rural Use

The history of irrigation in Callahan, Comanche, Eastland, and Erath Counties began in the early 1950's at a slow uniform rate largely as a result of the drought years. By the end of 1963, about 180 irrigation wells were supplied from the Antlers and Travis Peak Formations. In 1964 and 1965, irrigation in the area began to accelerate due to the development of an efficient submersible pump and government price supports for peanuts. These wells are pumped about 60 to 70 days annually and the water is generally used to irrigate peanuts and bermuda grass.

Between 1958 and 1984, the amount of ground water pumped for irrigation in this area increased from 2,914 to 39,408 acre-feet (Texas Water Development Board, 1986). During this time period the number of acres irrigated increased from 3,834 to 67,966 and the number of irrigation wells actually in operation increased from 90 to 2655. In 1984 Comanche County had the largest number of irrigation wells actually in operation in the four-county area.

Industrial

For the purpose of this report industrial use includes manufacturing, power supply, and mining. In 1985, approximately 4,202 acre-feet was pumped from the Trinity Group aquifer for industrial purposes. This was a little over 5 percent of the total amount. The largest use of ground water from the Trinity Group aquifer in the categories of manufacturing (1,771 acre-feet) and power (356 acre-feet) occurred in McLennan County. Somervell County was the largest user of ground water for mining from the Trinity Group aquifer, pumping approximately 291 acre-feet.

Domestic and Livestock

The amount of ground water pumped from all aquifers within the study area for rural domestic and livestock purposes in 1985 was approximately 18,000 acre-feet. This represents about 22 percent of the total amount of ground water used from all aquifers.

Projected Water Demands, 1990-2010

The total amount of both ground and surface water used in the study area for 1980 was estimated at 206,914 acre-feet, and for 1985, 205,852 acre-feet (Texas Water Development Board, 1988). Of these totals, 46 percent in 1980 and 45 percent in 1985 were for municipal use, 36 percent and 37 percent for irrigation use, a little less than 8 percent in both years for power generation, 3 percent in both years for manufacturing, less than 1 percent in both years for mining operations, and 7 percent in both years for livestock use. Current and projected water demands for the study area are shown in Table 3.

Projections of future municipal and rural requirements are based upon the 1988 Texas Water Development Board Revised Data Series population projection and projected demands per capita water use. Future projections of irrigation, industrial, and livestock use are based upon projected demands and the apportioned share of total county demands. Projections take into account the demands that are likely to occur during drought conditions.

Under projected conditions, the total annual water requirement for the study area is expected to increase by 40 percent from 1985 to the

Table 3
Historical and Projected Demands for Ground and Surface Water in the Study Area (Units in Acre-feet)

	1980	1985	1 990*	2000*	2010*
Municipal Use					
Major Cities [1]					
Ground	15,088	13,486			
Surface`	64,819	60,553			
Sub-Total	79,907	74,039	92,837	97,152	102,882
County Other [2]					
Ground	12,832	13,428			
Surface	2,275	5,091			
Sub-Total	15,107	18,519	22,631	24,526	26,571
Municipal Use:					
Total	95,014	92,558	115,468	121,678	129,453
Other uses [3]					
Ground	40,923	54,016			
Surface	70,977	59,278			
Total	111,900	113,294	149,589	155,229	158,309
Study Area					
Ground	68,843	80,930			
Surface	138,071	124,922			
Total	206,914	205,852	265,057	276,907	287,762

1 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.

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

3 Includes irrigation, manufacturing, power, mining, and livestock.

* Includes Ground and Surface water.

year 2010, at which time the annual demand is estimated to be 287,762 acre-feet. Municipal and rural requirements are expected to increase by 40 percent to 129,453 acre-feet by the year 2010. The greatest projected increase occurs in the category of power, which will inflate 158 percent to 39,500 acre-feet by 2010. This increase in water demand will begin sometime in 1990 when the Comanche Peak Nuclear Power Plant in Somervell County becomes operational. Most of the water demand will be from surface water, which will be transported from Lake Grandbury to the Comanche Peak cooling reservoir. The next major increase in water use will be from manufacturing with an increase of 120 percent. Mining use is expected to increase by 103 percent, and livestock use by 37 percent. Again, these projections are based on drought condition requirements. Actual water demand may never reach this level.

AVAILABILITY OF WATER

Current Availability of Ground Water

The recoverable volume of fresh to slightly saline ground water in storage for the Trinity Group aquifer within the study area was a little less than 202,000 acre-feet in 1980, with an estimated annual effective recharge to the Trinity Group aquifer of a little over 26,000 acre-feet per year. The availability in the study area in each river basin was modified from the Department's Report 238, "Ground-Water Availability in Texas". A little less than 77,000 acre-feet of ground water was pumped from the Trinity Group aquifer in 1985, so that the annual withdrawal by pumpage far exceeds the replenished quantity, resulting in water-level declines in the artesian portion of the aquifer as shown in Figures 11 through 14.

Availability of Surface Water

At the present time, there are 10 surface-water reservoirs in the study area with storage capacities greater than 5,000 acre-feet. These 10 reservoirs have a total water supply storage capacity of 1,467,304 acre-feet and have a combination surface area of 54,935 acres. These reservoirs are estimated to be able to supply 296,400 acre-feet of water under 2010 conditions of sediment deposition. All of this water, with the exception of 3,615 acre-feet, is currently committed to supply needs in the study area and other areas of the Brazos River basin.

Surface-water supplies could be increased with the development of the Bosque and Paluxy projects and the reallocation of storage in Lakes Waco and Whitney. An additional 176,000 acre-feet of supplies could be developed with these projects, increasing the 2010 supply to a total of 472,400 acre-feet.

Surface-water supplies are more than adequate to meet the projected needs of the study area through the year 2010. However, entities that will experience a shortage of water will have to negotiate with those entities that have a surplus to meet their needs.

Potential for Conjunctive Use of Ground and Surface Water

Conjunctive use ideally involves management of both ground and surface-water resources (Figure 20) 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 could be derived from such an arrangement. Historically, however, there has been little incentive for conjunctive use. The availability of ample supplies of ground water at the point of use with minimal investment has favored its development over surface supplies, particulary during the first half of this century. Since water wells could supply all needs, there was little justification for cities, towns, and industries to finance expensive surface reservoirs, transmission lines, and water treatment facilities. The trend away from ground-water sources to surface water has accelerated during the past 20 years with the recognition that the Trinity aquifer cannot

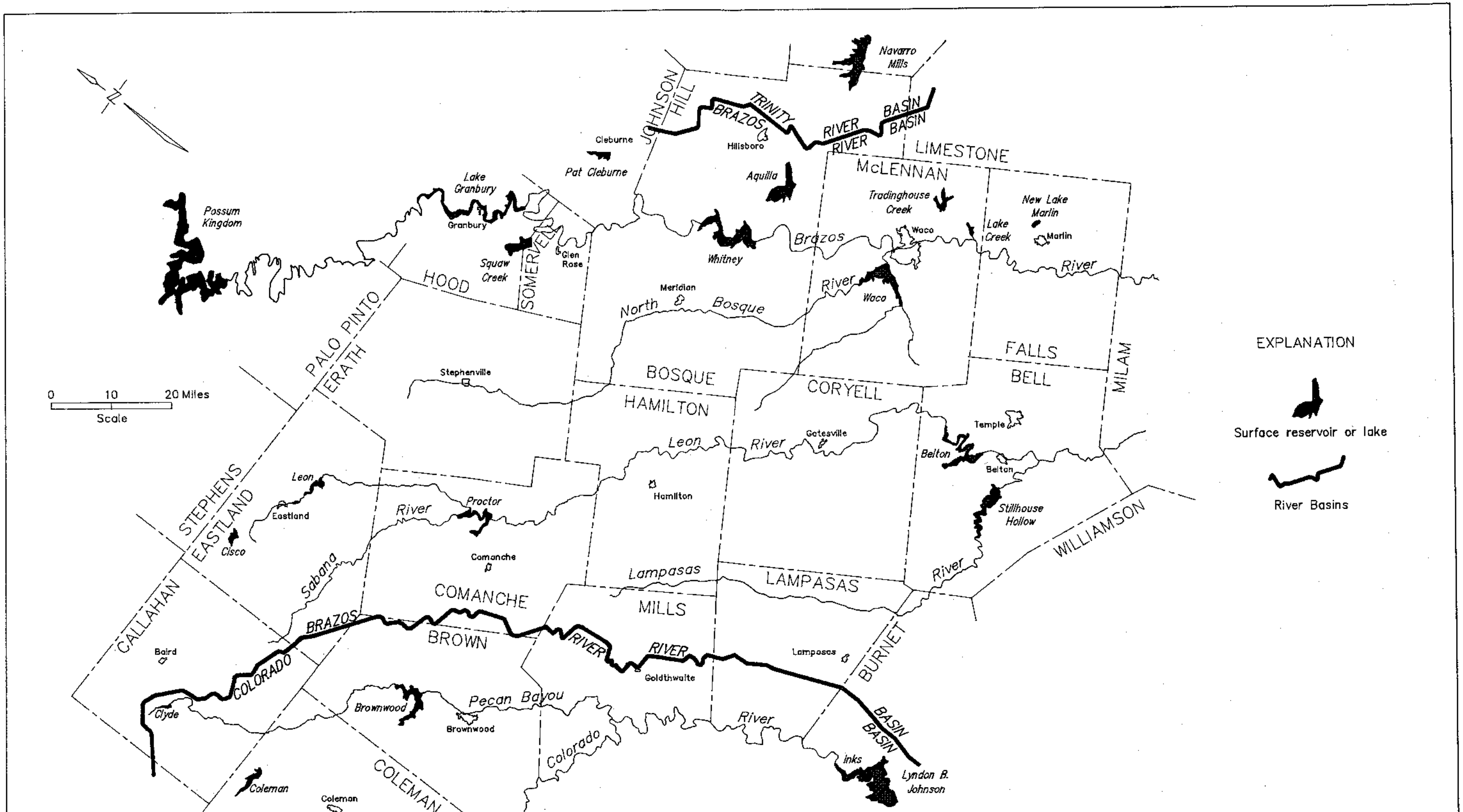


Figure 20

SURFACE RESERVOIRS AND RIVER BASINS

supply all the area needs. In particular, municipal users have moved to acquire surface water to assure future needs. Once financial resources are committed to acquire surface water and adequate supplies are assured, there is no incentive to incur the additional expense of maintaining water wells and pumping equipment. The wells are usually maintained as backup supply for a period of time, but are eventually abandoned.

Conjunctive use is currently practiced to some small degree in the study area. Of the 46 major cities or towns (over 1,000 population) in the area, seven reported using both ground and surface sources to supply their needs in 1985. Additionally, some cities supplied by ground water have contracts to purchase emergency supplies from other users with surface sources.

A number of factors tend to limit the potential for conjunctive use of ground and surface waters in the study area. Some of the factors listed below are legal in nature, some physical, and some economic.

(1) Because two opposing doctrines of water law are applied to surface and ground-water sources, no single authority exists to manage the development and distribution of the total resource.

(2) The common practice of requiring that the total amount of surface water supplied under contract be paid for, whether used or not, offers little incentive for the user to conserve the surface water or adopt a conjunctive use program.

(3) The aquifer has relatively low transmissive and storage characteristics. Consequently, the aquifer's potential for supplying large quantities of water in times of prolonged surface-water shortages is limited.

(4) Unless shortages dictate, it is unlikely that individual users will voluntarily acquire and maintain both a ground and surface-water supply because of the costs.

Areas Favorable For Future Development of Ground Water

The areas where limited development of ground water is feasible in the near future in the downdip (confined) part of the study area were determined by delineating areas where the hydrostatic head or water levels of the Hosston Member were less than 500 feet below the land surface and at least 100 feet above the top of the Hosston Member (Figure 21); no consideration was given to water quality for this determination. Innumerable discharge points between the aquifer outcrop and the downdip limit of the fresh to slightly saline water are assumed, and due consideration is given to the low transmissivity of the aquifer and to pumping lift costs (modified from Muller and Price, 1979, p. 13). Favorable areas in and near the outcrop depend upon the saturated thickness of the aquifer which may vary over relatively short distances. No attempt is made to delineate favorable or unfavorable areas in the outcrop.

The most favorable area is a narrow band extending in a southerly direction through Somervell, Erath, Bosque, Hamilton, and Coryell Counties just downdip from the outcrop as shown on Figure 21. Currently, the Hensell Member is the primary production zone in this area, although the deeper Hosston Member could supply ample quantities of fresh water with only moderate increases in lift costs. The existing Hensell wells could be deepened to utilize the Hosston thereby enhancing both water quality and well yields.

Bell County was experiencing large water-level declines until the Temple-Belton area began using surface water. Since then, declines have slowed and the vast majority of Bell County is a favorable area for ground-water development, providing that surface water continues to be used in conjunction with any additional development.

The area adjacent to the "bad water line" shown in Figure 21 is delineated as favorable, but wells are very deep (some in excess of 3700 feet), and have thermal problems associated with ground-water temperatures as high as 60°C (140°F). Water quality also varies due to extensive faulting in this area.

Potential Methods of Increasing Aquifer Recharge

Factors which determine the amount of recharge to the aquifer include the amount and frequency of precipitation, areal extent of the outcrop, topography, type and amount of vegetation and condition of the soil cover in the outcrop, and permeability of the aquifer.

Increased recharge would benefit the area by increasing the amount of water in storage in the Trinity Group aquifer which has experienced significant water-level declines, particularly in the downdip or confined part of the aquifer.

Outcrop (Unconfined) Areas

Numerous methods which enhance the recharge process (artificial recharge) have been studied (O'Hare and others, 1986). The most effective methods of increasing recharge include the use of runoff control structures in the outcrop, which in effect increases the time of contact between surface runoff and the aquifer, allowing the runoff water to percolate downward to the water table. Control structures which might be effective in the outcrop areas include check dams, pits, furrows, ditches, and field terracing. Spreading ponds might be utilized in some locales as a means of recharging treated sewage or excess surface water if available. In addition, brush control programs and grassland development could enhance recharge where brush infestation is a problem.

The capacity of the aquifer to accept recharge has been demonstrated at two localities in Erath and Comanche Counties (Nordstrom, 1987), where over a two year period, 97 percent of the precipitation was retained by the soil. This percentage includes the amount returned to the atmosphere as evaportranspiration and the amount that reaches the water table as recharge. Klemt and others, (1975), estimated that 4 percent of the annual precipitation is recharged to the aquifer. Nordstrom also concluded that up to 20 percent of the water applied to irrigated crops in the area is returned to the aquifer as recharge.

Although more than one-half of the total volume of water currently withdrawn from the Trinity aquifer in the study area is pumped from wells in the outcrop, there is no indication that a long-term, net depletion of water in storage is occurring in the outcrop area. In the future, if the volume of water withdrawn increases, discharge may

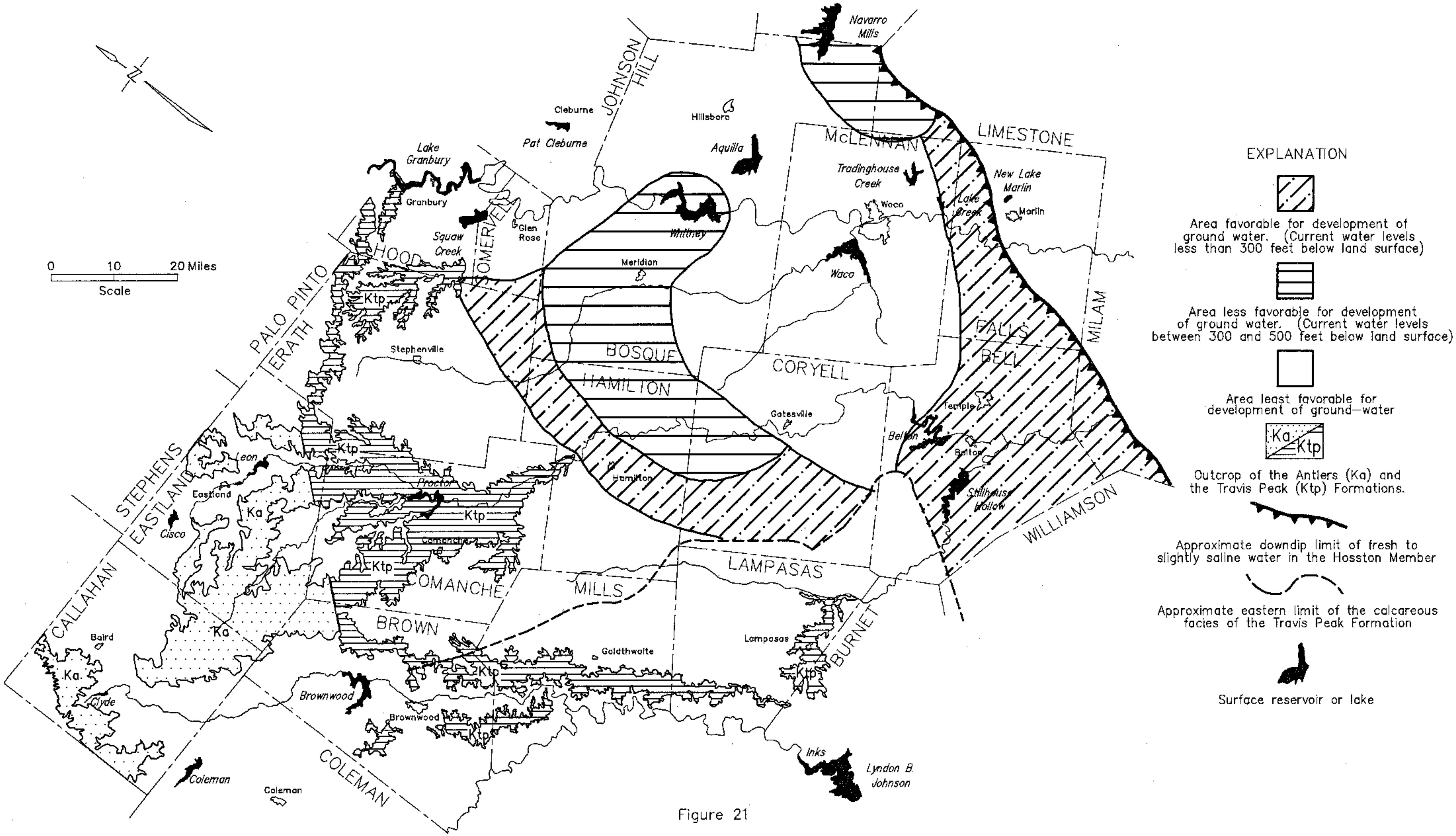


Figure 21

AREAS FAVORABLE FOR FUTURE DEVELOPMENT OF GROUND WATER

exceed recharge and depletion of the aquifer may begin. Should these conditions occur some of the above methods of increasing recharge may prove beneficial in maintaining the water supply by off-setting the overdraft.

Downdip (Confined) Areas

Runoff control structures are not applicable in the downdip or confined portions of the aquifer where depths to the top of the aquifer vary from a few feet near the outcrop to more than 3,000 feet in the most downdip areas. Recharge to the aquifer in these areas would require the use of injection wells. Although recharge in the areas of large water-level decline would be desirable, a number of factors, including technical, economical, and political are involved. Before using injection wells, a surface-water source must be available which equals or exceeds quality standards. The injected surface water must be compatible with the ground water from both a chemical and temperature standpoint to avoid the possibility of undesirable precipitates forming in the injection well and surrounding aquifer.

In addition, the storage capacities of confined aquifers such as the Trinity Group are relatively small compared to water-table or unconfined aquifers.

Assuming that surface water is available for recharge, initial capitol costs for injection wells and treatment plants as well as annual operation and maintenance costs are likely to be large.

If injection wells prove feasible both technically and economically, some type of entity would be required to manage the project to assure optimum operation and to regulate future development in the area.

Projected Availability Through the Year 2010

The amount of ground water needed to supply projected demands through the year 2010 exceeds the estimated annual effective recharge to the aquifer. As previously mentioned the average annual effective recharge to the Trinity Group aquifer within the study area was estimated to be a little over 26,000 acre-feet. In 1985, a little over 34,000 acre-feet of ground water was pumped from the Trinity Group aquifer in the downdip area for municipal, manufacturing, irrigation, power, mining, and livestock purposes. With the 1980 population of the study area forecasted to increase 30 percent by the year 2000, and 48 percent by the year 2010, the water demands will increase accordingly. Because the available ground-water supply from the Trinity Group aquifer is insufficient to meet even current levels of demand in the study area indefinitely, an increase in the amount of surface water use is needed to meet future demands.

Most of the counties within the study area lie in the Brazos River basin. Portions of Brown, Callahan, Comanche, Eastland, Lampasas, and Mills are in the Brazos and Colorado River basins. Hill County is in part of the Brazos and Trinity River basins. The locations of the surface-water reservoirs and boundaries of the river basins in the study area are shown in Figure 20.

The Brazos River basin has existing and proposed surface-water development sufficient to meet projected surface-water requirements for all purposes in the study area other than irrigated agriculture through the year 2010.

Although the study area has sufficient surface water to meet projected municipal and manufacturing needs through 2010, localized shortages could occur by 1990 largely due to a continued reliance on ground water from the Trinity Group aquifer. Also, cities such as Goldthwaite (Mills County) that obtain surface water from rivers are restricted to the amount of surface water that can be obtained by the amount of flow in the river. The cities of Stephenville and Glen Rose and areas in Erath County will get surface water from the proposed Paluxy Reservoir. The permit for water rights is currently in litigation.

Additional surface-water supplies will also be required to meet municipal and industrial needs in McLennan and Bosque Counties. The cities of Clifton and Meridian in Bosque County and other cities surrounding Waco are anticipated to be supplied surface water with the proposed construction of Lake Bosque on the North Bosque River and by raising the surface elevation of the conservation pool in Lake Waco. This permit process is ongoing.

The rapidly expanding population and associated municipal and manufacturing surface-water requirements within Coryell and Bell Counties, including the requirements for Fort Hood and the Brazos River System, are projected to exceed the dependable yield of Lake Belton by 2010. Large portions of the yields of both Lake Belton and Stillhouse Hollow are presently used to meet water-supply needs in the lower Brazos basin.

The Brazos River Authority is looking at several sites outside the study area to supply downstream needs now being met by Lake Belton and Stillhouse Hollow, thereby freeing up their total yields for local needs in the study area.

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