Texas Water Development Board

Report 339

Evaluation of the Ground-Water Resources of the Paleozoic and Cretaceous Aquifers in the Hill Country of Central Texas

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ABSTRACT

The evaluation of the ground-water resources of a part of the Hill Country area of central Texas includes all or part of Bandera, Blanco, Comal, Gillespie, Hays, Kendall, Kerr, Medina, and Travis Counties. This report was prepared in response to the Sixty-ninth Texas Legislature's passage of House Bill 2 which stipulated the identification and study of areas within the State that are experiencing or expected to experience within the next 20 years critical ground-water problems.

The relatively extensive study area of all or parts of nine counties has a subhumid to semiarid climate that has low to moderate rainfall and high rates of evaporation. The economy of the area is dominated by agribusiness related to the raising of livestock and exotic game animals, tourism, and hunting, and is significantly influenced by the population and economic growth conditions associated with the metropolitan centers at San Antonio, New Braunfels, San Marcos, and Austin.

In 1985, about 62 percent of the water supplies in the area were obtained from the Paleozoic and Cretaceous aquifers. The Paleozoic aquifers include the Hickory and Mid-Cambrian aquifers of Cambrian age, the Ellenburger-San Saba aquifer of Cambrian and Ordovician age, and the Marble Falls aquifer of Pennsylvanian age. The aquifers of Cretaceous age include the Lower Trinity, Middle Trinity, Upper Trinity, and Edwards Plateau aquifers.

The average annual recharge to the Paleozoic and Cretaceous aquifers was estimated to be about 450,000 acre-feet. However, because of the erratic occurrence of ground waters within these aquifers and their inherently low to extremely low coefficients of transmissibility and storage, only about 46,000 acre-feet of ground water has been estimated as the annual sustained yield of these aquifers in the study area. Of the 18,739 acre-feet of ground water used in 1985, approximately 74 percent was used for drinking and household purposes (public and domestic uses).

Historical development of ground water in areas of concentrated withdrawals for public water supply purposes has caused adverse water-level declines, and in some cases the potential for encroachment of poorer quality water and base flow depletion in nearby effluent streams. Adverse water-level declines associated with centers of concentrated withdrawals for public water supply purposes from the Lower Trinity aquifer has caused increases in pumping lifts and corresponding decreases in well yields and drastic depletion of available drawdown. Such water-level decline in areas of concentrated withdrawal in the Middle Trinity aquifer has caused serious reductions in the aquifer's transmissibility and a corresponding decrease in well yields. As well yields decrease, more wells are needed to meet increasing demands.

Conjunctive use of ground water and surface water has been and is currently being successfully practiced at Kerrville, Boerne, and Johnson City. Other public water systems, particularly at Bandera, Comfort, Fredericksburg, Ingram, Blanco, Woodcreek, and Wimberly, should establish conjunctive use programs or seek and develop the additional but limited ground-water supplies available in remote areas away from current centers of pumpage. In either case, additional water development to meet the increasing water demands expected for the study area through the year 2010 will be costly.

From 1980 to 1985, population increased at a rate of about five percent per year. Similar population increases are expected to occur from 1985 to the year 2010 at an annual rate of about three percent. These historical and projected population increases readily demonstrate that the study area will need additional water supplies for drinking and household purposes (public and domestic uses). From 1985 to 2010, water use for such purposes is expected to increase from about 22,872 acre-feet per year to about 47,380 acre-feet per year, a four percent increase per year.

Unusually high to excessive concentrations of nitrate have been detected in the ground waters produced from the shallow portions of the Paleozoic and Cretaceous aquifers. The aquifers most effected by this nitrate pollution include the Edwards Plateau, Upper Trinity, Middle Trinity, Marble Falls, Ellenburger-San Saba, and Hickory aquifers. Except for the Edwards Plateau aquifer, such nitrate pollution seems to be limited to scattered local areas, and is believed to be associated with improper disposal of human and/or animal wastes. The nitrate pollution of the Edwards Plateau aquifer was detected in relatively widespread areas of western Gillespie and northwestern Bandera Counties, and is believed to be associated with non-point source pollution from livestock and wildlife excrements. Such nitrate pollution of the Edwards Plateau aquifer was detected to be increasing, and poses a threat to the water quality of the base flow to the upper portions of the Pedernales, Guadalupe, Medina, and Sabinal Rivers in the western part of the study area. Unusually high to excessive concentrations of fluoride and sulfate were detected in the Trinity Group aquifers. Such inherent concentrations of fluoride are found mainly in the deeper portions of the Lower Trinity aquifer. Regional to local occurrences of anhydrite and gypsum beds in the Glen Rose Formation and the Cow Creek member of the Travis Peak Formation are the sources of the unusually high to excessive concentrations of sulfate found in ground waters produced from the Upper and Middle Trinity aquifers. In most cases, these inherent concentrations of sulfate can be avoided by proper well construction; particularly by the setting and proper cementing of sufficient casing through the upper unit of the Glen Rose Formation.

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INTRODUCTION

Purpose

In 1985, the Sixty-ninth Texas Legislature recognized that certain areas of the State were experiencing or were expected to experience, within the next 20 years, critical ground-water problems. House Bill 2 was enacted which directed the Texas Department of Water Resources to identify the critical ground-water areas, conduct studies in those areas, and submit its findings and recommendations on whether a ground-water conservation district should be established in the respective areas to address the ground-water problems (Subchapter C, Chapter 52, Texas Water Code).

This study of the Hill Country area was conducted to address and evaluate the ground-water problems related to adverse water-level declines and quality deterioration with respect to the Paleozoic and Cretaceous aquifers in all or part of nine counties in central Texas. Discussions of the characteristics and relationships of these aquifers and their relationships to the surface-water regime, a perspective on the amounts of ground water available on a perennial basis and on a sustained basis, and the expected water requirements of the area to the year 2010 are included.

Location and Extent

The Hill Country study area is located as delineated on Figure 1, and is composed of all of Gillespie, Blanco, Kerr, Bandera, and Kendall Counties and parts of Travis, Hays, Comal, and Medina Counties. The area includes the southeastern portion of the Edwards Plateau in Gillespie, Kerr, Kendall, and Bandera Counties; extends eastward to the Colorado River in Travis County and southward and southeastward to the northeastern edge of the Balcones fault zone in Travis, Hays, Comal, and Medina Counties. The area consist of 5,539 square miles within portions of the Colorado, Guadalupe, San Antonio, and Nueces River basins.

Geographic Setting

The land surface is characterized by a rough and rolling terrain. The nearly flat-lying, erosion-resistive carbonate rocks of the Edwards Formation which form the surface of the Edwards Plateau in the western portion of the study area have been deeply incised into the less resistive, marly carbonate rocks of the Glen Rose Formation. The terrain within the Nueces River basin in southwestern Bandera and northern Medina Counties is comprised of highly dissected divides and incised stream valleys. Most of the terrain within the San Antonio, Guadalupe and Colorado River basins is comprised mainly of broad valleys and narrow divides (Ashworth, 1983). Elevations generally range from about 2,300 feet above mean sea level in western Kerr and northwestern Bandera Counties to about 700 to 800 feet above mean sea level to the east in Hays and Travis Counties.

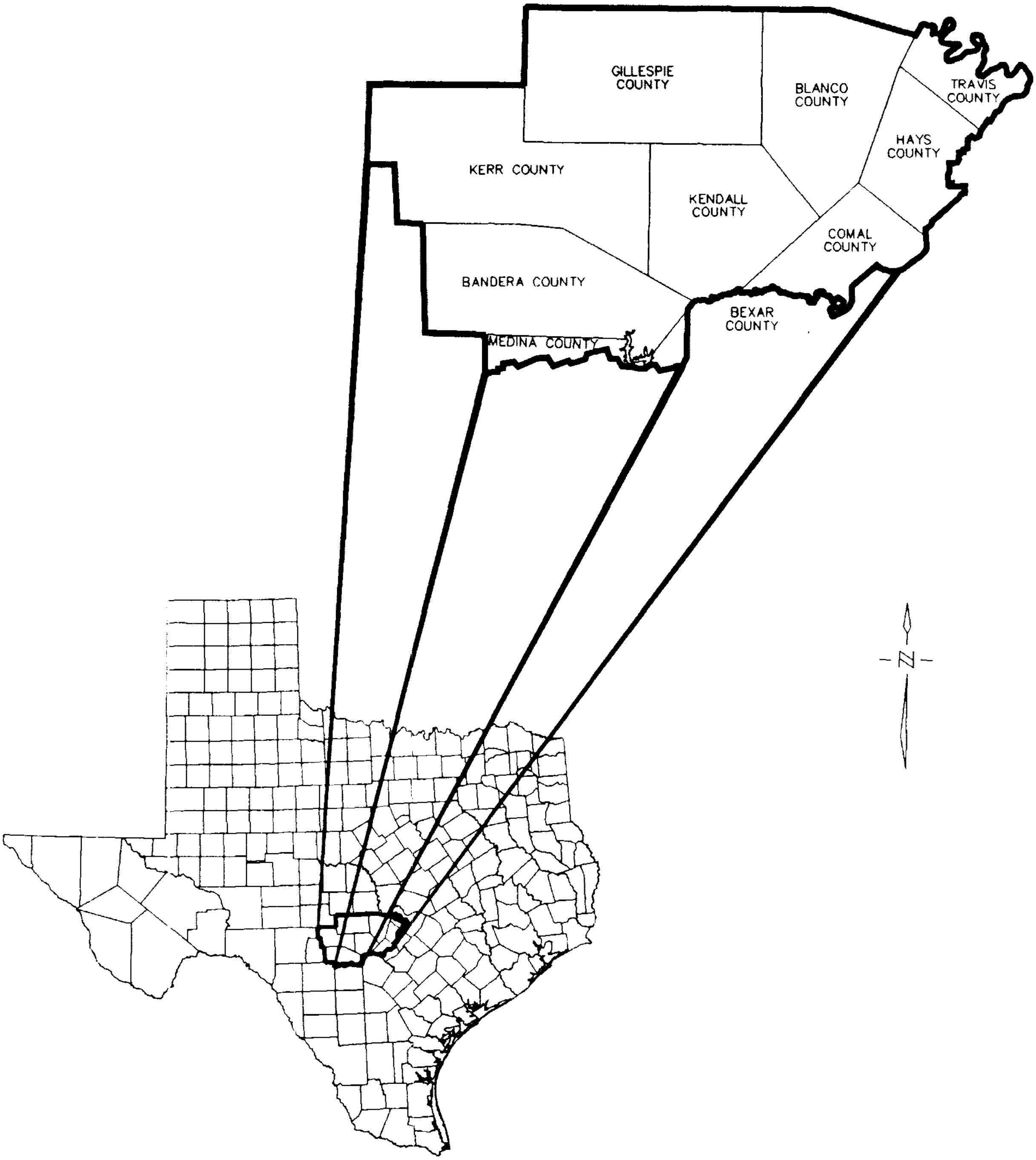


Figure 1

LOCATION OF HILL COUNTRY STUDY AREA

Drainage in the Nueces River basin is generally to the south in the Sabinal River and Seco, Hondo, and Verde Creeks in Bandera and Medina Counties. Drainage in the San Antonio River basin is to the southeast in the Medina River in Bandera County and to the east and southeast in Cibolo Creek in Kendall and Comal Counties. The Guadalupe River and Blanco River which generally flow eastward are the major streams draining the Guadalupe River basin. The Colorado River basin portion of the study area is drained mainly by the Pedernales River which generally flows eastward in Gillespie and Blanco Counties and into the Colorado River at Lake Travis in western Travis County. Parts of Travis and Hays Counties are drained by Barton and Onion Creeks which are within the Colorado River basin.

The Pedernales, Blanco, Guadalupe, and Medina Rivers are dominantly effluent streams which receive large amounts of base flow from ground water naturally discharged from the Paleozoic and Cretaceous aquifers. The tributaries of these major streams are characterized by two dominant types; namely, the perennial spring-fed streams and the intermittent streams that only transport storm runoff. A very significant amount of the flows in the Sabinal and Medina Rivers and Seco, Hondo, Verde, and Cibolo Creeks are diverted underground as they cross the Balcones fault zone immediately adjacent to the southern portion of the study area. Those flows which are so diverted become recharge to the Edwards (Balcones Fault Zone) aquifer and are naturally discharged from the aquifer as base flow to the Guadalupe River, mainly at Comal Springs at New Braunfels in Comal County outside the study area and at San Marcos (Aquarena) Springs at San Marcos in Hays County outside the study area.

Economy and Land Use

The economy of the Hill Country area is based primarily on the raising of domestic livestock and exotic game animals. Also, the economy is influenced by a significant, commuting labor force which is employed outside the study area in and near San Antonio, New Braunfels, San Marcos, and Austin. Significant income is generated from hunting, tourism, private camps, and resorts. Because of its ruggedness and scenic beauty, the area also has and will continue to have a very significant retirement population that directly supports the economy. Some incomes are derived from the cutting of cedar for fence posts and from the quarring of building stone.

Most of the rural land in the Hill Country area is used for the raising of domestic livestock and exotic game animals. These rural lands are extensively used to support the hunting of wild game and imported exotic game animals. Use of the land for hunting has greatly increased in the last 30 years, and probably rivals the raising of domestic livestock for ranching income and payment of land taxes. On the other hand, the great population growth within the last 30 years has caused urban development of the land. Numerous rural residential subdivisions are most concentrated in eastern Bandera and northwestern Medina Counties, particularly around Medina Lake; along and adjacent to Interstate Highway 10 in Kendall and Kerr Counties; in Comal County on and adjacent to Canyon Lake; in Hays County near Wimberley and Dripping Springs; and in Travis County along Lake Travis, State Highway 71 West, and U.S. Highway 290 West.

Because of the limited supply of ground water, the limited amounts of productive soils, and the rising cost of fuel, there is very little irrigation in the study area, although trickle irrigation systems are gaining popularity for watering orchards and vineyards; particularly in Gillespie County. The most productive soils are found in the floodplain areas of the Pedernales, Blanco, Guadalupe and Medina Rivers and some of their tributaries and on the outcrops of the Hickory sandstone and Hensell sand in Gillespie and Blanco Counties. The detailed descriptions and characterizations of the soils in the study area are provided by Werchan, Lowther and Ramsey (1974) for Travis County, Allison, Dittmar and Hensell (1975) for Gillespie County, Dittmar, Deike and Richmond (1977) for Medina County, Hensell, Dittmar and Taylor (1977) for Bandera County, Dittemore and Allison (1979) for Blanco County, Dittemore and Hensell (1981) for Kendall County, Batte (1984) for Comal and Hays Counties, and Dittemore and Coburn (1986) for Kerr County.

Vegetation

A variety of vegetation inhabits the Hill Country. Prairie grasses and stands of Live and Spanish Oak grow on the karstic surface of the upper plateau. "Cedar" (scrub Juniper) and Live Oak are prominent in the marly dissected region. Lining the banks of the creeks and rivers are Cypress trees while the terraces support growths of Live and Post Oak, "Cedar", Elm, Hackberry, Cottonwood, Sycamore, and Willow. Varieties of natural grasses include Little Bluestem, Indian Grass, Sideoats Grama, and Texas Winter Grass. The most common introduced grasses include Coastal Bermuda, Plains Lovegrass, Klein Grass, and King Ranch Bluestem (Cuyler, 1931).

A number of studies have shown that grasses utilize one-third to one-half as much water as trees and shrubs. Trees, such as the "Cedar" or Juniper, are especially inefficient water users. Several residents of the Hill Country have indicated that creeks and springs on their property have increased in flow since they converted their land from tree growth to grass.

Climate

A subhumid to semiarid climate prevails throughout the study area. The average annual precipitation ranges from about 33 inches in the east to about 24 inches in the west. During the drought period from 1950 to 1956, the average annual precipitation was about 22 inches. The distribution of average annual precipitation is provided on Figure 2 along with average monthly precipitation for periods of record at seven selected stations. According to this data, approximately 9.0 million acre-feet of precipitation falls on the study area on an average annual basis.

The average monthly temperature for the period 1951 to 1980 ranged from a minimum of 33°F in January in the northwest to a maximum of 96°F in July throughout most of the study region. The annual mean temperature for the period 1951 to 1980 ranged from 66°F in the northwest to 68°F in the east. The average annual gross lake-surface evaporation for the period 1950 to 1979 ranged from 69 inches in the northwest to 63 inches in the east, (Larkin and Bomar, 1983). These rates of evaporation are more than twice the average annual precipitation.

Previous Investigations

County ground-water investigations have been conducted in the study area by George (1952) in Comal County, Holt (1956) in Medina County, DeCook (1960) in Hays County, Reeves and Lee (1962) in Bandera County, Reeves (1967) in Kendall County, Reeves (1969) in Kerr County, Follett (1973) in Blanco County and Brune and Duffin (1983) in Travis County. The ground-water conditions in a portion of Gillespie County within and near the City of Fredericksburg was addressed by Mount (1963). Local ground-water conditions in and adjacent to selected communities have been addressed by Sundstrom, Broadhurst and Dwyer (1949) and Broadhurst, Sundstrom and Rowley (1950). A number of local water-availability studies for public supply purposes have been made by private consulting firms at the request of municipalities within the study area. Regional studies that addressed the ground-water resources of the study area include Lang (1953), Petitt and George (1956), Winslow and Kister (1956), Alexander, Myers and Dale 1964), Mount and others (1967), Duffin (1974), Walker (1979), Guyton (1979), and Muller and Price (1979). Ashworth (1983) specifically addressed the Trinity Group aquifers in most of the study area and provided valuable data and information for this study and report.

Important regional studies that address the geological conditions within the study area include Hill and Vaughan (1898), Hill (1901), Sellards, Adkins and Plummer (1932), Sellards and Baker (1934), Imlay (1945), Cloud and Barnes (1946), Barnes (1948), Lozo and Stricklin (1956), Flawn (1956), Barnes and others (1959), Lozo and others (1959), Flawn and others (1961), Young (1962), Fisher and Rodda (1967), Young (1967), Stricklin, Smith and Lozo (1971), Rose (1972) and Barnes and Bell (1977). The geologic maps presented in this report were adapted from the Llano, San Antonio, Seguin, and Austin sheets of the Geologic Atlas of Texas (scale 1:250,000) which were published by the Bureau of Economic Geology (1974a, 1974b, 1974c, and 1981). Other important geologic maps of the area include Barnes (1952-1956) and Barnes (1963-1982).

Acknowledgements

The Texas Water Development Board and the author wish to thank the numerous individuals who cooperated in providing information on the aquifers in their area, and to the many property owners who allowed access to their wells to measure water levels and sample for chemical quality. Additionally, special thanks are given to a group of individuals who served on an advisory committee that was formed by the Board and the Texas Water Commission to provide a medium through which those most affected by the conditions of the aquifers in the study area could contribute to the study. The committee consisted of a small number of concerned and knowledgeable citizens who represent water users in the study area.

A special thanks to Wanda Cooper and Deborah Schultz for typing the manuscript report and also to Mark Hayes and Steve Gifford from the Computer Graphics Unit for the preparation of the illustrations. Paul McElhaney (Geologist) also helped in the preparation of various illustrations.

GROUND-WATER RESOURCES

Geological Setting

Stratigraphy

The stratigraphic sequence showing the position and relationship of the existing geological units at the surface and in the subsurface of the study area is given in Table 1 which provides the oldest geological unit at the bottom and the youngest geological unit at the top. Table 1 also provides the approximate range in thickness and character of rock (lithology) of each significant geological unit. Those units which occur at the surface are delineated in a generalized manner on the geologic map provided in Figure 3. The approximate delineations of the Paleozoic rocks (both Foreland Facies and Ouachita Facies) and the Precambrian rocks directly underlying the lowest occurring Cretaceous rocks in the study area are provided in Figure 4. Figures 5 and 6 provide side-view perspectives of the positions and relationships of the Cretaceous, Paleozoic and Precambrian rocks which occur at the surface and in the subsurface. The contact of the lowest occurring Cretaceous rocks with the underlying rocks is a prominent angular unconformity where steeply dipping, deformed, and truncated Paleozoic and older rocks underlie the more gently dipping, relatively undisturbed lower Cretaceous rocks.

Structure

The Llano uplift (Figure 7) is a structural high dome of igneous and metamorphic (metasedimentary) Precambrian rocks which occur at the surface and in the subsurface of the northern portion of the study area (Figures 4, 5, 7, and 8). Within northern Gillespie and northern Blanco Counties, local Precambrian granite highs of the Llano uplift have been identified and encountered as upward protruding "knobs" (monadnocks) which penetrate the Paleozoic Foreland Facies and Cretaceous rocks as shown at points A, B, C and D in Figure 8. Where these protruding "knobs" are present, normally occurring Paleozoic Foreland Facies and Cretaceous geological units may have reduced thicknesses or may be entirely absent. Well data and control in parts of Gillespie and Blanco Counties verify the occurrence of such subsurface upward protruding "knobs" as shown at points A, B, and D in Figure 8. Bear Mountain which is a granite outcrop at Palo Alto Creek and Highway 965 north of Fredericksburg is an example of an upward protruding "knob" which locally penetrates Paleozoic Foreland Facies and Cretaceous rocks in the area. The upward protruding "knob" illustrated at point C in Figure 8 generally illustrates the geological conditions at Bear Mountain.

The Cretaceous rocks (Table 1) consist of relatively gently dipping beds with some on-lapping of the lower beds onto the structurally high Paleozoic and Precambrian rocks associated with the Llano uplift (Figure 7). The dip of Cretaceous rocks in the northern and western part is generally to the south at about 10 to 15 feet per mile. In the southern downdip areas near the Balcones fault zone (Figure 7), the Cretaceous rocks are dipping to the south at about 100 feet per mile. The regional dip of Cretaceous rocks in the eastern part is to the east and southeast at about 100 feet per mile.

The Paleozoic Foreland Facies rocks (Table 1) which unconformably underlie the lower Cretaceous rocks and which flank the southern portion of the Llano uplift have significantly greater dips than the Cretaceous rocks. Dips of 400 to 900 feet per mile generally to the south and southeast are common. The steepest dipping beds are usually present where the Paleozoic rocks are effected by faulting and underlying, upward protruding Precambrian rocks. The regional strike of these rocks generally follows the domal shaped trend of the underlying Precambrian rocks of the Llano uplift. Figures 4, 5, 6, 7, and 8 present perspectives on the structural position and relationship of the various Paleozoic and Precambrian rocks underlying the Cretaceous rocks. One of the most prominent structural features are the thrust faults which placed the generally older Paleozoic and Precambrian (?) Ouachita Facies rocks (Table 1) over the generally younger Paleozoic Foreland Facies rocks in the deeper, downdip, subsurface portion of the study area (Figures 5 and 8).

The San Marcos arch (A in Figure 7 and lower portion of Figure 6) is a broad, southeast plunging anticlinal structure which is believed to be a subsurface extension of the Llano uplift to the northwest. The Cretaceous geological units overlying this anticlinal structure occur at higher elevations, and the various members of the Travis Peak Formation (Table 1) are significantly thinner on the northeastern flank of the arch in Hays and Travis Counties (Figure 6). Point D in Figure 8 generally illustrates the subsurface geological conditions associated with the San Marcos arch.

The Fredericksburg high (B in Figure 7) is a narrow subsurface ridge consisting of structurally high Precambrian and Paleozoic Foreland Facies rocks. It trends southwestward beneath Cretaceous rocks across the study area from the Llano uplift in northeastern Gillespie County to east-central Bandera County where it probably extends beneath the rocks of the Ouachita structural belt. This ridge-like pre-Cretaceous structure may be a narrow extension of the Llano uplift formed during late Paleozoic uplift and faulting. The northern portion of this structural high is represented by the undifferentiated Precambrian rocks directly underlying the Cretaceous rocks as shown on Figure 4 in the area trending southwestward from the Precambrian outcrop just west of Eckert in northeast Gillespie County to Fredericksburg in south central Gillespie County. Points A and B on Figure 8 generally illustrate the occurrence of this structural high northeast of Fredericksburg. The Precambrian granite outcrop at Bear Mountain north of Fredericksburg, is an upward protruding Precambrian "knob" (monadnock) that is a surface expression of this structural high (Point C in Figure 8). Geological control provided by several wells southwest of Fredericksburg in Gillespie, Kendall, Kerr and Bandera Counties indicates the apparent location and the extension of the Fredericksburg high to the Ouachita structural belt in Bandera County (Figure 7). This linear structural feature may be associated with the development of the San Marcos arch located to the east in Blanco, Comal, and Hays Counties (Figure 7).

During the Late Paleozoic to Early Mesozoic, the Paleozoic and Precambrian rocks were extensively faulted. In most of the study area, these faults are covered by Cretaceous deposits (Figures 5 and 6), and only become apparent through close study of available well data control. These faults are very evident in northeastern Gillespie County and northern Blanco County where the extensively faulted Paleozoic Foreland Facies and Precambrian rocks are exposed at the surface (Figure 4). The geological relationship of these faults is demonstrated on the left-hand portion of Figure 8. The two faults associated with point B on Figure 8 demonstrate an upthrown block

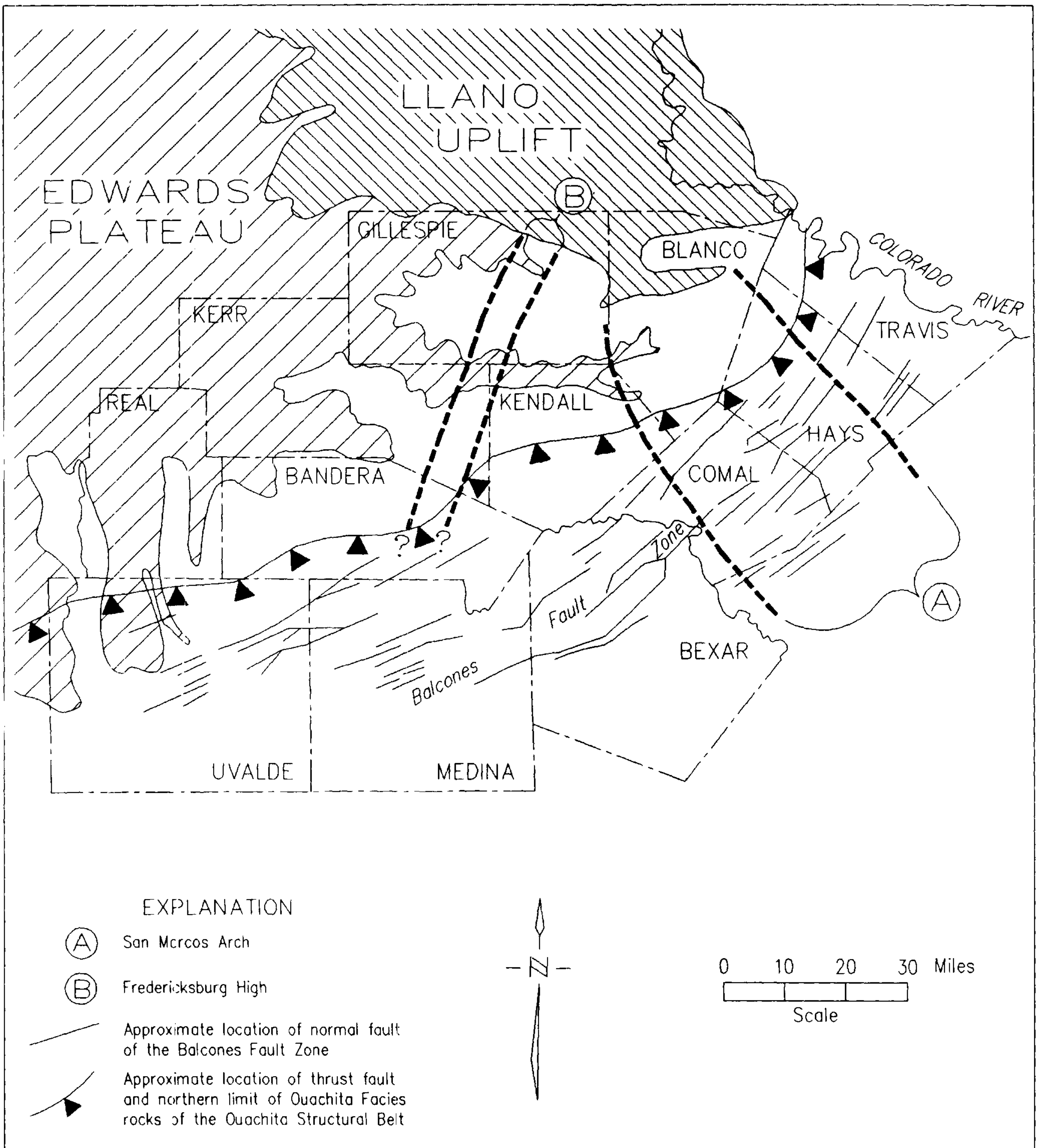
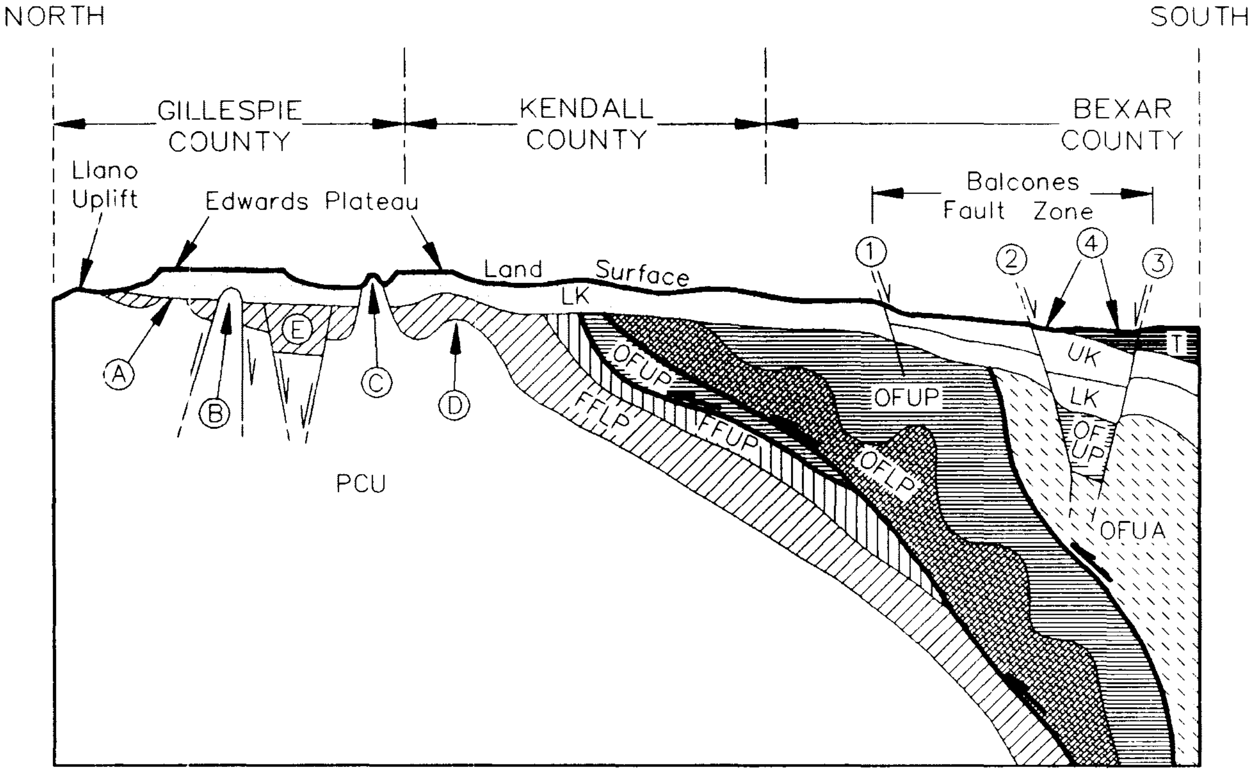


Figure 7

STRUCTURAL TRENDS



(Modified From Flawn,et al.,1961 and Barnes,et al.,1972)

EXPLANATION

T	Tertiary Rocks	FFLP	Foreland Facies Lower Paleozoic Rocks (Cambrian–Devonian)
UK LK	Upper Cretaceous Rocks Lower Cretaceous Rocks	OFLP	Ouachita Facies Lower Paleozoic Rocks(Cambrian?–Mississipian)
FFUP	Foreland Facies Upper Paleozoic Rocks (Mississipian–Pennsylvanian)	OFUA	Ouachita Facies Rocks of Unknown Age (Lower Paleozoic or Precambrian)
OFUP	Ouachita Facies Upper Paleozoic Rocks (Mississipian–Pennsylvanian)	PCU	Precambrian Rocks Undifferentiated
	Thrust Fault	or	Normal Faults

Figure 8

NORTH–SOUTH DIAGRAMATIC CROSS–SECTION

(horst), while the two faults associated with point E on Figure 8 demonstrate a downthrown block (graben). The faulted Paleozoic Foreland Facies and Precambrian rocks beneath the Cretaceous rocks in northern and central Gillespie County are shown in Figure 5. Most of the faults which displace the Paleozoic Foreland Facies rocks are high angle (steeply dipping), northeast-southwest and northwest-southeast striking normal faults which have some apparent strike-slip (lateral) displacement and which have associated, similarly oriented fractures or joints. The displacement by normal faulting ranges from a few feet to more than 2,000 feet. The apparent strike-slip (lateral) displacement of some of these faults in the Llano uplift region has been observed to range from a few feet to several miles. Also shown in Figures 5, 6 and 8 in the subsurface of central Kendall County and the northern portion of Bexar County are the thrust faults and folding associated with the deformed Ouachita Facies Paleozoic and Precambrian (?) rocks. The undifferentiated Precambrian rocks shown on Figure 8 were also greatly and extensively deformed during the Precambrian by metamorphism, granitic intrusion, folding, and faulting.

The Balcones fault zone (Figures 3, 5, 7, and 8) is a system of normal faults which generally strike northeast-southwest and disrupt the gently dipping Cretaceous rocks in Bandera, Medina, Bexar, Comal, Hays, and Travis Counties. The most significant faults displace the Cretaceous rocks about 200 to 700 feet. The downthrown side of most of the faults is toward the coast (faults 1 and 2 in Figure 8). This type of normal faulting developed a "stairstep" group of fault blocks with downward movement coastward. However, some of the faults have their downthrown side landward (fault 3 in Figure 8), and consequently form a graben (downthrown block 4 in Figure 8) in combination with faults with their downthrown side coastward (fault 2 in Figure 8). Study of well data control within the Balcones fault zone indicates that there are steeply dipping, transversing normal faults and perhaps some reverse faults within some of the major fault blocks.

Underground cavities of various sizes and shapes are common in the carbonate (limestone and dolomite) rocks of the Edwards Formation, the Glen Rose Formation, the Ellenburger Group, and the San Saba member of the Wilberns Formation (Table 1). These cavities were formed as ground water moved through faults and/or associated bedrock fractures or joints and removed carbonate and associated evaporitic rocks by dissolution. The larger cavities may extend vertically and laterally for great distances. They may be expressed at the land surface by sinkholes and sinkhole depressions which were formed by collapse when the cavities grew to such a large size as to no longer support their overburden. Sinkholes are found in streambeds flowing over the Glen Rose Formation, and sinkhole depressions are common on the Edwards Formation outcrop of the Edwards Plateau. Sinkholes and sinkhole depressions also are found in association with the outcrop and shallow subsurface occurrence of the Ellenburger Group and the San Saba member of the Wilberns Formation (Table 1 and Figure 4).

Delineation and Relationship of Aquifers

The Paleozoic aquifers pertinent to understanding the occurrence, availability and dependability of the ground-water resources of the study area are from oldest to youngest the Hickory, the Mid-Cambrian, the Ellenburger-San Saba, and the Marble Falls aquifers (Table 1). The important Cretaceous aquifers include the Lower Trinity, the Middle Trinity, the Upper Trinity, the Edwards Plateau, and the Edwards-Trinity (Plateau) aquifers (Table 1). The very local and minor water-bearing units which occur in rocks of Precambrian and Cenozoic age as indicated in Table 1 are not pertinent to describing the ground-water resources, consequently they will not be given further consideration in this report.

The lateral surface and subsurface extents of each of the Paleozoic aquifers are approximately delineated in Figure 4. The northern portion of this map generally shows the outcrops of the Precambrian and Paleozoic geological units provided in Table 1. The recharge areas for the Hickory, Mid-Cambrian, Ellenburger-San Saba, and Marble Falls aquifers occur within these outcrops in northern Gillespie and Blanco Counties and adjacent portions of Mason and Llano Counties. The approximate subsurface delineations of the Precambrian and Paleozoic geological units and the Paleozoic aquifers which underlie the Cretaceous rocks are shown in Figure 4. Also shown are the approximate downdip extents of slightly saline water in the Hickory and Ellenburger-San Saba aquifers, and the Ouachita Facies rocks that underlie the Cretaceous rocks in the Ouachita structural belt. The outcrops and general extent of the Cretaceous geological units and aquifers are shown in Figure 3. The vertical perspectives of the positions and relationships of the Paleozoic and Cretaceous aquifers are provided in Figures 5 and 6.

Hydrological Continuity of Aquifers

Hydrological continuity or connection of the Cretaceous and Paleozoic aquifers is very common throughout the Hill Country study area. In the large area where Cretaceous rocks overlie the Paleozoic rocks (Figures 3 and 4), the Hensell sand member (Middle Trinity aquifer) and the Hosston sand member (Lower Trinity aquifer) are hydrologically connected to the Hickory, Mid-Cambrian, Ellenburger-San Saba, and Marble Falls aquifers. Figure 5 illustrates the hydrologic continuity of the Hensell sand with the Hickory sandstone, Welge sandstone and undifferentiated rocks of the Ellenburger Group in Gillespie and Kendall Counties, and the Hosston sand with the undifferentiated rocks of the Ellenburger Group and Marble Falls Formation in Kendall County.

Throughout most of the area where the upper unit of the Glen Rose Formation (Table 1) overlies the lower unit of the Glen Rose Formation (Table 1), the Upper Trinity aquifer and Middle Trinity aquifer are in hydrological continuity (Figures 5 and 6). These aquifers have been differentiated because they have very different water-quality characteristics. The Upper Trinity aquifer has significant beds of anhydrite and gypsum which cause most of the water to be unusually high in sulfate content and slightly to moderately saline. The Middle Trinity aquifer has very little anhydrite and gypsum, and consequently, much better water quality. Even though the Hammett shale member is considered to be a consistently occurring confining bed throughout the study area (Figures 5 and 6), the Lower Trinity and Middle Trinity aquifers are also hydrologically connected. Hydrogeologically, the three aquifers of the Trinity Group, namely the Lower, Middle, and Upper should be considered a leaky aquifer system. Where the Edwards Formation overlies all or part of the Trinity Group aquifers in the Edwards Plateau portion of the study area, the Edwards Plateau aquifer becomes part of the leaky aquifer system forming the Edwards-Trinity (Plateau) aquifer (Figures 5 and 6).

As indicated in Table 1, Mississippian and Devonian rocks are known to function as confining beds separating the Ellenburger-San Saba aquifer and Marble Falls aquifer. However, these Mississippian and Devonian rocks occur as thin, scattered, remanent deposits, and where absent the Ellenburger-San Saba aquifer and the Marble Falls aquifer are hydrologically connected.

The late Paleozoic faulting and associated fracturing displaced Paleozoic Foreland Facies rocks thousands of feet in parts of the study area (Figures 5 and 8). Under these conditions, Paleozoic aquifers were positioned opposite each other and are considered to be hydrologically connected. An example of this condition is illustrated by the large fault which has greatly displaced the Paleozoic Foreland Facies rocks near and beneath the Pedernales River on Figure 5. In this example, the Welge and Lion Mountain sandstones and the Hickory sandstone have been positioned by faulting opposite the Ellenburger Group; thus providing an opportunity for hydrological continuity of the Mid-Cambrian and Hickory aquifers with the Ellenburger-San Saba aquifer. Also, such faulting of Paleozoic Foreland Facies rocks has provided displaced and fractured zones through which ground-water of one aquifer is able to flow under differential head conditions to another aquifer even though they are not positioned opposite each other.

Recharge, Movement And Discharge of Ground Water

On an average annual basis, the study area receives about 9.0 million acre-feet of rain fall. Of this amount only about 450,000 acre-feet per year or 5 percent directly recharges the Paleozoic and Cretaceous aquifers by infiltration of rainfall and seepage of stream runoff in the outcrop areas of the aquifers. The outcrops of the various geological units which contain the Paleozoic and Cretaceous aquifers are delineated on Figures 3 and 4.

Direct recharge to the Paleozoic aquifers is relatively small because of the limited extents of their outcrops in northern Gillespie and Blanco Counties (Figure 4). Consequently, the Paleozoic aquifers only receive about 12,300 acre-feet per year or about 2.7 percent of the estimated total annual direct recharge (450,000 acre-feet per year). Of this amount, about 8,600 acre-feet is recharge to the Ellenburger-San Saba aquifer, about 2,800 acre-feet is recharge to the Hickory aquifer, about 600 acre-feet per year is recharge to the Mid-Cambrian aquifer and about 300 acre-feet is recharge to the Marble Falls aquifer. These estimated amounts of natural direct recharge do not include the recharge of the Paleozoic aquifers in the large area where they are overlain by Cretaceous rocks. Where the Paleozoic aquifers underlie the Cretaceous rocks, they are readily recharged by downward movement of ground waters from the overlying Hensell sand member and Hosston sand member of the Travis Peak Formation (Figure 5).

Since the outcrops of the Edwards Formation, the Glen Rose Formation, and part of the Travis Peak Formation of the Trinity Group occur in most of the study area (Figure 3), the Cretaceous aquifers receive about 97.3 percent or about 437,700 acre-feet of the total average annual direct recharge in the study area. Of this amount, 124,500 acre-feet is recharge to the Edwards Plateau aquifer, and 313,200 acre-feet is recharge to the Upper and Middle Trinity aquifers. Since the Sligo and Hosston members of the Travis Peak Formation do not significantly outcrop in the study area (Figure

5), the Lower Trinity aquifer is recharged by downward movement of ground water from the Middle Trinity aquifer. The Upper and Middle Trinity aquifers also are locally recharged by an unknown amount of seepage from Medina Lake (Bandera and Medina Counties), Canyon Lake (Comal County), and Lake Travis (Travis County) (Figure 4).

Ground water in the Paleozoic and Cretaceous aquifers moves slowly under the influence of gravity from areas with relatively high water-level elevations to areas with relatively low water-level elevations, and generally from areas of recharge to areas of discharge. The direction and rate of ground-water movement in these aquifers under natural conditions are controlled 1) by the hydraulic gradient (water-level dip), 2) by the amounts and distribution of rock permeability, 3) by the dip of the rock and its bedding plane, and 4) by faults and fractures. The direction and rate of natural movement is readily changed when the hydraulic gradient is altered by the withdrawals from wells.

Adequate amounts of data are not available to determine accurately the direction or rate of movement of the water in the Paleozoic aquifers. However, water in these aquifers probably moves southward and southeastward along the dip of the aquifers. In some areas of Gillespie and Blanco Counties, a significant portion of the recharge probably moves into the Middle Trinity aquifer and discharges into the Pedernales River and its tributaries. Consequently, the general directions of ground-water movement in the Pedernales River Valley of Gillespie and Blanco Counties as shown in Figure 9 probably represent the general directions of ground-water movement in the Paleozoic aquifers under these conditions. This condition is particularly apparent for the Ellenburger-San Saba aquifer in the Pedernales River Valley of eastern Gillespie County and northern Blanco County. In other cases, water moves into the artesian portions of the Paleozoic aquifers and continues to move slowly downdip to the south and southeast. Rates of ground-water movement of 100 to 400 feet per year can be expected for the Hickory aquifer, and probably as much as 1,000 feet per year or more in honeycombed and cavernous limestones and dolomites of the Ellenburger-San Saba aquifer.

Ground-water movement in the Lower Trinity aquifer is indicated by Ashworth (1983) in parts of Kerr, Kendall, and Bandera Counties. In this part of the study area, water in the aquifer moves southeastward in Kendall County and southwestward in Kerr and Bandera Counties. The ground-water divide indicated just north and west of Interstate Highway 10 could be shifted further to the west to coincide with the Fredericksburg high (Figure 7).

The general directions of ground-water movement in the Middle Trinity aquifer are indicated on Figure 9. Water in the aquifer on a regional basis generally moves to the south, southeast, and east. However, water movement in the aquifer is clearly indicated toward the Medina River in eastern Bandera County; Cibolo Creek in southern Kendall County; the Guadalupe River in eastern Kerr, central Kendall, and central Comal Counties; the Blanco River in southern Blanco and western Hays Counties; and the Pedernales River in Gillespie and Blanco Counties. The ground-water divides delineated in Figure 9 generally coincide with the topographic divides or basin boundaries of the major streams. The general directions of ground-water movement in the Upper Trinity aquifer probably coincide with the directions of movement shown in Figure 9.

Ground-water movement in the Edwards Plateau aquifer is indicated for the northwestern and western portions of the study area in Walker (1979). Water in the aquifer is moving from areas of high water-level elevations, or areas of recharge, to areas of low water-level elevations where ground water is discharged to numerous springs and seeps and by evapotranspiration along the edge of the Edwards Plateau (Figure 7), primarily in western Gillespie County, northern Kendall County, and northwestern Bandera County (Figure 3).

Ground water is naturally discharged from the Paleozoic and Cretaceous aquifers by numerous springs, by channel seepage associated with the base flow of effluent streams, by subsurface underflow out of the study area, and by evapotranspiration to the atmosphere. Ground water is artificially discharged from the aquifers by numerous wells which are pumped to supply water needed for public supply, rural domestic, irrigation, and livestock watering purposes.

Previous ground-water studies and field investigations have inventoried many of the springs which discharge from the Paleozoic and Cretaceous aquifers. The flows of these springs fluctuate due to variable rainfall. The flow of most of the springs is usually low or may cease during periods of low rainfall, and is usually very high during periods of excessive rainfall. Table 2 provides distribution of flow information for 173 springs which have been inventoried in the study area.

Some of the prominent springs which have estimated and measured flows in gallons per minute (gpm) are provided in Table 3. These and the many other springs plus stream-channel seepage from the aquifers contribute to the base flow of the effluent streams in the study area.

Those streams which have stream flow gages and estimated amounts of base flow are the Pedernales River, Blanco River, Guadalupe River, Cibolo Creek, Medina River, Hondo Creek, Seco Creek and Sabinal River (Figure 9). The total average or mean annual base flow estimated from the gaged flows of these streams is about 369,100 acre-feet per year. This amount equates to about 2.00 inches per year or about 6.7 percent of the mean annual rainfall (30.0 inches per year).

This amount of mean annual apparent base flow is considered to be a liberal estimate and has not been adjusted for human activities; namely, ground-water pumpage, diversions of stream flow, municipal and irrigation return flows, and retention structures which cause retained water to be lost to evapotranspiration. However, this mean annual base flow estimate does provide a very reasonable perspective on the mean annual amounts of ground-water being discharged from and recharged to the aquifers.

Annual base flow or ground-water discharge can vary considerably depending on the amount, frequency, and distribution of annual rainfall. As an example, in 1956 during an extreme drought, the estimated base flow was only about 18,800 acre-feet which equates to only about 0.07 inches of the 1956 annual rainfall. On the other hand, in 1975 during a very wet period, the base flow was estimated to be about 1.32 million acre-feet which equates to about 4.57 inches of the 1975 annual rainfall. An interpretation of rainfall and base-flow data and information provided by Kuniansky (1989) for a period having above normal rainfall indicates that from December 1974 through March 1977 (28 months) the mean annual base flow was about 1.03 million acre-feet or about 10.8 percent of the annual rainfall.

Table 2. Distribution of Reported Spring Flows

		Distribution by Flow Catagories in Gallons Per Minute				
Aquifer	**Number Inventoried**	**5 or less**	**6 to 20**	**21 to 100**	**101 to 500**	**More than 500**
Hickory	5	2	1	1	1	0
Percent	100%	40%	20%	20%	20%	0
Mid-Cambrian	2	1	1	0	0	0
Percent	100%	50%	50%	—	—	—
Ellenburger-San Saba	13	4	3	3	2	1
Percent	100%	31%	23%	23%	15%	8%
Marble Falls	0	0	0	0	0	0
Percent	—	—	—	—	—	—
Total Paleozoic	20	7	5	4	3	1
Percent	100%	35%	25%	20%	15%	5%
Lower Trinity	0	0	0	0	0	0
Percent	—	—	—	—	—	—
Middle Trinity	38	1	7	17	6	7
Percent	100%	3%	18%	45%	16%	18%
Upper Trinity	54	10	24	19	1	0
Percent	100%	19%	44%	35%	2%	—
Edwards Plateau	61	14	19	19	5	4
Percent	100%	23%	31%	31%	8%	7%
Total Cretaceous	153	25	50	55	12	11
Percent	100%	16%	33%	36%	8%	7%
Total Study Area	173	32	55	59	15	12
Percent	100%	18%	32%	34%	9%	7%

Table 3. Flow of Prominent Springs

Aquifer	County	Spring Name and Location	Estimated* or Measured** Flow gpm	Year
Hickory	Blanco	Buffalo Spring on Buffalo Creek	500*	1941
Ellenburger-San Saba	Blanco	Crofts Spring on Salter Springs Creek	60** 1,650**	1938 1968
Ellenburger-San Saba	Blanco	Hobbs Spring on Pedernales River	471**	1969
Ellenburger-San Saba	Gillespie	Lange Mill Spring into Threadgill Creek	400*	1984
Middle Trinity	Comal	Rebecca Creek Spring into Guadalupe River	1,750* 300*	1943 1976
Middle Trinity	Comal	Spring Branch Spring into Guadalupe River	5,000*	1945
Middle Trinity	Comal	Honey Creek Spring into Guadalupe River	1,250*	1944
Middle Trinity	Comal	Big Spring on Guadalupe River (under Canyon Lake)	1,750**	1938
Middle Trinity	Comal	Two unnamed springs on Guadalupe River (under Canyon Lake)	6,300*	1944
Middle Trinity	Comal	Bear Creek Spring into Guadalupe River	200* 2,250*	1943 1945
Middle Trinity	Hays	Jacob's Well Spring on Cypress Creek	1,070*	1955
Middle Trinity	Kendall	Harwell Springs (4 springs) on Curry Creek	178** 1,110**	1940 1964
Edwards Plateau	Gillespie	Headwater Spring of Pedernales River near Harper	1,000* 9,000*	1936 1960
Edwards Plateau	Gillespie	Trough Spring on Trough Spring Creek	2,000* 480**	1961 1970
Edwards Plateau	Gillespie	Pape Spring on Klein Branch Creek	1,500* 310*	1960 1970
Edwards Plateau	Kerr	Ellebracht Spring near Mountain Home	500*	1966
Edwards Plateau	Kerr	Fish Hatchery Spring near Mountain Home	2,500*	1966

Ashworth (1983) indicates that recharge of the Trinity Group aquifers approximately equates to 4 percent of the mean or average annual rainfall. Using 4 percent as a conservative estimate, the mean annual apparent base flow of 369,100 acre-feet would equate to about 223,700 acre-feet for the gaged area and about 349,100 acre-feet for the total Hill Country study area. On the other hand, by using the 2.00 inches per year (6.7 percent of mean annual rainfall) as a liberal consideration, the study area would have a mean annual apparent base flow of 577,200 acre-feet. Therefore, the mean annual ground-water discharge as base flow to area effluent streams probably ranges from about 249,100 acre-feet (4 percent of mean annual rainfall) to about 577,200 acre-feet (6.7 percent of mean annual rainfall). For this report, it is reasonable to assume that the mean annual ground-water discharge as base flow to area effluent streams equates to about 432,000 acre-feet per year (5 percent of mean annual rainfall).

In addition to ground water discharged as base flow, ground water is discharged as subsurface underflow beneath the eastern, southeastern, and southern boundaries of the study area. Interpretation of data and information provided by Ashworth (1983) indicates that this underflow discharge may be about 18,000 acre-feet per year. This amount reasonably correlates with estimates of underflow from the Glen Rose Formation to the Edwards (Balcones Fault Zone) aquifer determined by Lowry (1955).

Therefore, the mean annual amount of ground water being discharged from the study area is about 450,000 acre-feet per year with about 432,000 acre-feet per year as base flow to area effluent streams and 18,000 acre-feet per year as subsurface underflow. Without consideration to discharge by evapotranspiration, it is reasonable to assume that this is the total estimated amount of mean annual net recharge received by the main zones of saturation of the Paleozoic and Cretaceous aquifers.

Sufficient data and an accurate methodology are not available to reasonably determine the amount of ground water being discharged by evapotranspiration. However, this type of discharge is likely to be very high, probably hundreds of thousands of acre-feet per year.

Ground water is discharged from the Paleozoic and Cretaceous aquifer by numerous wells used for public supply, rural domestic, manufacturing, irrigation, and livestock watering purposes. For these purposes, approximately 17,828 acre-feet was withdrawn by wells in 1980, and approximately 18,739 acre-feet was withdrawn by wells in 1985. Approximately 71 to 74 percent of the water withdrawn by wells has been used for public supply and rural domestic purposes for drinking, lawn watering, gardening, and other household uses.

The largest ground-water withdrawals from the Paleozoic aquifers are by the City of Fredericksburg and the City of Johnson City. The City of Fredericksburg withdraws ground water from the Hickory, Ellenburger-San Saba, and Middle Trinity aquifers. The City of Johnson City withdraws ground water from the Ellenburger-San Saba aquifer. Significant amounts of ground water are withdrawn from the Paleozoic aquifers in Gillespie and Blanco Counties for use by rural residential subdivisions and unincorporated communities. The Trinity Group aquifers provide all or part of the water supply for such communities as Bandera, Dripping Springs, Boerne, Comfort, and Kerrville. The Trinity Group aquifers also supply significant amounts of ground water to many rural residential subdivisions and unincorporated communities located in Bandera, Kerr, Kendall, Comal, Hays, and Travis Counties.

Aquifer Hydraulic Characteristics

The quantity of water that an aquifer contains and will yield to wells depends on its hydraulic characteristics. These important characteristics include porosity and the coefficients of storage (including specific yield), permeability and transmissibility.

Table 4 provides a reasonable perspective of available representative hydraulic characteristics estimated for geological units of the Paleozoic and Cretaceous aquifers in and adjacent to the study area. The laboratory porosity data was obtained from the Texas Water Development Board's laboratory files and are the result of core testing for various ground-water investigations. The hydraulic characteristics determined from pumping test were compiled from data and information given in Alexander and others (1964), Ashworth (1983), Brune and Duffin (1983), Follett (1973), Guyton (1973), Meyers (1969), Mount (1963), Mount and others (1967), Reeves (1967), Reeves (1969), Sieh (1975), and Walker (1979).

All or most of the characteristics for the Hickory, Ellenburger-San Saba and Edwards (Balcones Fault Zone) aquifers given in Table 4 are from test wells in areas immediately adjacent to the study area. However, they are considered to be representative characteristics which are intended to provide a reasonable perspective of such hydraulic characteristics of the respective aquifers within the study area.

Because most of the fresh to slightly saline ground water in carbonate aquifers occurs in solution-formed openings which are not uniform and which may be very erratic in size and distribution, the actual hydraulic characteristics of such aquifers are usually extremely variable. Therefore, the hydraulic characteristics determined at any one well or well field cannot be considered to accurately represent such characteristics for the aquifer throughout its extent. Because of this condition of non-uniformity of hydraulic characteristics, a quantitative determination of storage and yield of such carbonate, water-bearing geological units such as the Ellenburger Group, San Saba limestone, Sligo limestone, Cow Creek limestone, Glen Rose Formation and Edwards Formation (Table 1) should be used with caution, and only as approximations.

As indicated in Table 4, the hydraulic characteristics of the Trinity Group aquifers are inherently deficient, having comparatively small to very small coefficients of storage and transmissibility. Because of these deficiencies, most Trinity Group aquifer wells experience unusually large drawdowns, serious reduction in well yields, and relatively poor water-level recovery after extended periods of pumping. These conditions are particularly evident within and near centers of concentrated ground-water withdrawals utilized for public water supply purposes.

Productivity of Wells

The productivity of a well is determined by the measurement of its yield and specific capacity. Yield is the volume of water discharged from a well per unit of time, and is measured as a pumping rate in gallons per minute (gpm). Specific capacity of a well is its yield (gpm) per unit of drawdown in feet (ft), and is expressed as gallons per minute per foot (gpm/ft) of drawdown Specific capacity of a well is most meaningfully measured after a specific duration of pumping time has elapsed. The drawdown and yield are measured simultaneously and the specific capacity is calculated by dividing the yield (gpm) by the drawdown (ft). Specific capacity of a well changes with changes in pumping time and well discharge, and decreases when pumping time, well discharge and drawdown increase (Driscoll, 1986).

Within the study area, the yields of wells and springs (see previous section on spring flows) may be described according to the following classification:

Range In Yields By Catagories (gpm)	**Classification of Yield Catagories**
5 or less	Very Small
6 to 20	Small
21 to 100	Moderate
101 to 500	Large
More than 500	Very Large

The well inventories, which were conducted during previous ground-water investigations and during a very limited supplemental investigation for this study, provided the yields of 2,152 wells completed in the Paleozoic and Cretaceous aquifers. Such inventoried yields consist of those measured during various investigations and those estimated and reported by water well drillers, well operators and well owners. Table 5 provides a perspective on the 2,152 yields inventoried by giving the distribution by yield catagories, by aquifer, and by county or groups of counties. Also provided by aquifer is the maximum yield reported, weighted average yield, the percent that is weighted average or greater, and the percent that is greater than 20 gpm. A general perspective on the chance or probability of the amount of well yield that may be expected from the Paleozoic and Cretaceous aquifers can be determined approximately by area from the data tabulated in Table 5.

The "Weighted Average Yields" calculated and shown for the Paleozoic and Cretaceous aquifers in Table 5 generally indicate the aquifers having the most and least productive wells. The Paleozoic aquifers in order of most to least productivity by weighted average well yield are the Ellenburger-San Saba (65 gpm), Hickory (40 gpm), Marble Falls (35 gpm) and the Mid-Cambrian (20 gpm). The Cretaceous aquifers in order of most to least productivity by weighted average well yield are the Lower Trinity (230 gpm), Middle Trinity (55 gpm), Upper Trinity (25 gpm) and the Edwards Plateau (15 gpm). The well yields used in Table 5 for the Cretaceous aquifers include those well yields determined after acidizing.

The following discussions which are provided by aquifer include the probability of well yields that can be expected. Such probability is expressed as a percentage of the total number of well yields that were inventoried for each aquifer historically as indicated in Table 5. Some of the percent probabilities in the following discussions have been rounded to the nearest percent from the percentages given for each aquifer in Table 5. If a yield or yield category has an 80 percent probability, then it should be assumed that 80 out of 100 wells to be completed in the future will have that yield or have a yield that will fall within the specified yield category.

Table 4. Approximate Range in Representative Hydraulic Characteristics of the Paleozoic and Cretaceous Aquifers

Tests Aquifer	Geological Units	Laboratory Porosity of Core (% Vol.)	Approximate Results Determined from Pumping		
			Coef. of Storage (Dimensionless)	Permeability (gpd/ft^2)	Transmissibility (gpd/ft)
Hickory	Hickory Sandstone Member	3-42	0.0001-0.00004	38-1,038	5,000-44,000
Ellenburger-San Saba	San Saba Limestone Member	1-8	—	—	126,000
do	Ellenburger Group	1-17	0.0022	550-678	56,000-96,000
Lower Trinity	Hosston Sand and Sligo Limestone Members	1-29	0.00002-0.00005	5-268	150-25,000
Middle Trinity	Cow Creek Limestone Member	5-38	—	49	3,300
do	Hensell Sand Member	11-34	0.0000008-0.00005	5-9	600-1,100
do	Lower Unit-Glen Rose Fm.	9-28	0.000002	47-115	700-9,300
Upper Trinity	Upper Unit Glen Rose Fm.	3-20	—	—	1,500
Edwards (Balcones Fault Zone)	Edwards Formation	3-26	0.0004-0.020	4-877	1,900-386,000

Hickory Aquifer - Approximately 85 percent of the wells to be completed in the Hickory aquifer in Blanco and Gillespie Counties may be expected to have small to moderate yields. Only about 22 percent may be expected to yield 40 gpm or more, while about 41 percent may provide a yield greater than 20 gpm. Wells completed for rural domestic and/or livestock watering purposes have been reported to yield about 1 to 170 gpm. Historically, Hickory wells used for public supply have yielded about 200 to 790 gpm, while irrigation wells have been reported to produce 25 to 327 gpm.

Mid-Cambrian Aquifer - Approximately 50 percent of the wells to be completed in the Mid-Cambrian aquifer in Blanco and Gillespie Counties may be expected to have small yields. Approximately 53 percent may be expected to yield 20 gpm or more, while 32 percent may yield more than 20 gpm. Consequently, 21 percent of the wells may be expected to yield about 20 gpm. Wells completed for rural domestic and/or livestock watering purposes have been reported to yield about 1 to 50 gpm. The largest historical well yield was 60 gpm obtained in a public supply test well in south-central Gillespie County.

Ellenburger-San Saba Aquifer - Approximately 82 percent of the wells to be completed in the Ellenburger-San Saba aquifer in or near the Pedernales River Valley of Blanco and Gillespie Counties may be expected to have small to moderate yields. Approximately 10 percent probably will yield more than 100 gpm, while 19 percent may yield 65 gpm or more, and 55 percent may yield more than 20 gpm. Wells completed for rural domestic and/or livestock watering purposes have been reported to yield about 1 to 500 gpm. Historically, Ellenburger-San Saba wells tested and/or used for public supply have yielded about 14 to 1,500 gpm, while irrigation wells have been reported to produce about 20 to 610 gpm.

Marble Falls Aquifer - Approximately 63 percent of the wells to be completed in the Marble Falls aquifer in parts of eastern Gillespie County and eastern Blanco County may be expected to have very small to small yields. Approximately 25 percent may yield 35 gpm or more, while 37 percent may yield more than 20 gpm. Wells completed for rural domestic and/or livestock watering purposes have been reported to yield about 1 to 100 gpm. Historically, Marble Falls wells have not been used for public supply purposes. Irrigation wells have been reported to produce about 100 to 200 gpm.

Lower Trinity Aquifer - Approximately 60 percent of the wells to be completed in the Lower Trinity aquifer may be expected to have small to moderate yields. About 18 percent may yield 230 gpm or more, while 66 percent may yield more than 20 gpm. The most productive yields can be expected to occur in Bandera and Kerr Counties and portions of western Kendall County, where the weighted average yield was determined to be about 415 gpm. Wells completed for rural domestic and/or livestock watering purposes have been reported to yield about 3 to 275 gpm. Historically, Lower Trinity wells used for public supply have yielded about 10 to 1,400 gpm, while irrigation wells have been reported to produce about 25 to 1,100 gpm. Well yields have been significantly increased by acidizing.

Middle Trinity Aquifer -Approximately 76 percent of the wells to be completed in the Middle Trinity aquifer may be expected to have small to moderate yields. About 17 percent may yield 55 gpm or more, while 42 percent may yield more than 20 gpm. The most productive yields can be expected to occur in Kerr, Bandera, northern Medina, and western Hays

Table 5. Approximate Distribution of Well Yields by Aquifer

		Distribution By Yield Catagories (gpm) By Number (No.) and Percent (%)									
Aquifer	County(s)	Number of Yields (No./%)	5 or Less gpm (No./%)	6 to 20 gpm (No./%)	21 to 100 gpm (No./%)	101 to 500 gpm (No./%)	More Than 500 gpm (No./%)	Maximum Yield (gpm)	Weighted Average Yield (gpm)	Percent That Is Weighted Average or Greater	Percent Greater Than 20 gpm
Hickory	Blanco and Gillespie	343/100	42/12.2	159/46.4	132/38.5	9/2.6	1/0.3	790	40	22	41
Mid-Cambrian	Blanco and Gillespie	34/100	6/17.6	17/50.0	11/32.4	0/0	0/0	60	20	53	32
Ellenburger-San Saba	Blanco and Gillespie	585/100	45/7.7	217/37.1	263/44.9	56/9.6	4/0.7	1,500	65	19	55
Marble Falls	Blanco and Gillespie	32/100	10/31.3	10/31.3	9/28.0	3/9.4	0/0	200	35	25	37
Lower Trinity	Bandera, Kendall and Kerr	41/100	1/2.4	6/14.6	10/24.4	10/24.4	14/34.2	1,400	415	34	83
Lower Trinity	Bexar, Comal, Hays and Travis	52/100	2/3.9	23/44.2	17/32.7	10/19.2	0/0	205	55	27	52
Total Lower Trinity	Study Area	93/100	3/3.2	29/31.2	27/29.0	20/21.5	14/15.1	1,400	230	18	66
Middle Trinity	Bandera	72/100	3/4.2	42/58.3	17/23.6	8/11.1	2/2.8	700	70	14	38
Middle Trinity and Medina	Bexar	12/100	0/0	3/25.0	6/50.0	2/18.8	1/6.2	723	135	25	75
Middle Trinity	Blanco	103/100	37/35.9	54/52.4	12/11.7	0.0	0/0	90	15	28	12
Middle Trinity	Comal	62/100	2/3.2	32/51.6	24/38.7	4/6.5	0/0	250	40	27	45
Middle Trinity	Gillespie	139/100	18/13.0	48/34.5	67/48.2	6/4.3	0/0	350	45	14	53

Table 5. Approximate Distribution of Well Yields by Aquifer - *(continued)*

Distribution By Yield Catagories (gpm) By Number (No.) and Percent (%)											
Aquifer	**County(s)**	**Number of Yields (No./%)**	**5 or Less gpm (No./%)**	**6 to 20 gpm (No./%)**	**21 to 100 gpm (No./%)**	**101 to 500 gpm (No./%)**	**More Than 500 gpm (No./%)**	**Maximum Yield (gpm)**	**Weighted Average Yield (gpm)**	**Percent That Is Weighted Average or Greater**	**Percent Greater Than 20 gpm**
Middle Trinity	Hays	34/100	0/0	9/26.5	14/41.2	11/32.3	0/0	500	125	32	74
Middle Trinity	Kendall	128/100	21/16.4	56/43.8	41/32.0	10/7.8	0/0	350	45	17	40
Middle Trinity	Kerr	55/100	4/7.3	8/14.5	27/49.1	14/25.5	2/3.6	1,000	135	18	78
Middle Trinity	Travis	61/100	14/23.0	37/60.6	10/16.4	0/0	0/0	100	20	30	16
Total Middle Trinity	Study Area	666/100	99/14.9	289/43.4	218/32.7	55/8.2	5/0.8	1,000	55	17	42
Upper Trinity	Bandera, Kendall, Kerr and Medina	36/100	14/38.8	15/41.7	5/13.9	1/2.8	1/2.8	1,000	45	11	20
Upper Trinity	Blanco, Comal, Hays and Travis	94/100	24/25.5	57/60.6	12/12.8	1/1.1	0/0	175	20	19	14
Total Upper Trinity	Study Area	130/100	38/29.2	72/55.4	17/13.1	2/1.5	1/0.8	1,000	25	13	15
Edwards Plateau	Bandera, Gillespie, Kerr and Medina	269/100	69/25.6	178/66.2	22/8.2	0/0	0/0	60	15	42	8

Counties. Wells completed for rural domestic and/or livestock watering purposes have been reported to yield about 1 to 320 gpm. Historically, Middle Trinity wells used for public supply have yielded about 3 to 500 gpm, while irrigation wells have been reported to produce about 14 to 1,000 gpm. Well yields have been significantly increased by acidizing.

Upper Trinity Aquifer - Approximately 55 percent of the wells to be completed in the Upper Trinity aquifer may be expected to have small yields. Only about 13 percent may yield 25 gpm or more, while 15 percent may yield more than 20 gpm. The most productive yields can be expected to occur in Bandera, Kendall, Kerr, and northern Medina counties. Wells completed for rural domestic and/or livestock watering purposes have been reported to yield about 1 to 71 gpm. Historically, Upper Trinity wells used for public supply have produced up to 175 gpm, while irrigation wells have been reported to produce up to 1,000 gpm.

Edwards Plateau Aquifer - Approximately 92 percent of the wells to be completed in the Edwards Plateau aquifer may be expected to have very small to small yields. About 42 percent may yield 15 gpm or more, while only about 8 percent may yield 20 gpm or more. Well yields have been reported to range from 1 to 60 gpm for wells used for rural domestic and/or livestock watering purposes. Two irrigation wells are known to have been completed in the Edwards Plateau aquifer in north-central Gillespie County. The yields of these two wells are unknown at this time. An Edwards Plateau aquifer well is used as part of the public supply for a rural residential subdivision in western Gillespie County. The yield of this well is unknown at this time.

Historically the enhancement or increase of well yield by acidizing has been accomplished with apparent success in Lower and Middle Trinity aquifer wells in Bandera, Comal, Kendall, Kerr, and Travis Counties. Where the aquifer is contained in carbonate rocks or in calcareous sandstone and conglomerate, the yields and specific capacities (discussed later) of wells tapping such rocks may be increased by the controlled injection of diluted hydrochloric acid into the well bore. The acid increases the permeability of the aquifer by enlarging the openings, joints and/or solution channels in the immediate vicinity of the well bore. This process increases the effective well diameter, thereby increasing the yield of the well per unit of drawdown (specific capacity) (Reeves, 1967 and Reeves, 1969). Before the acidizing of a well is undertaken, it is recommended that representative samples of the water-bearing rocks from the well bore be collected and submitted for laboratory solubility tests to determine if acidizing will be effective.

Data reported for nine Lower Trinity aquifer wells indicates that acidizing provided well yields that were about 1.5 to 4.8 times greater than the well yields before acidizing. The average or mean of the well yields after acidizing was about 2.0 times greater than the average or mean of the well yields before acidizing. The median from such data indicates that the acidized well yields were about 3.1 times greater. These operations for the Lower Trinity aquifer were reported to have used 2,000 to 30,000 gallons per well of dilute hydrochloric acid.

Data reported for ten Middle Trinity aquifer wells indicates that acidizing provided well yields that were about 1.5 to 5.5 times greater than the well yields before acidizing. The average or mean of the well yields after acidizing was about 2.9 times greater than the average or mean of the well yields before acidizing. The median from such data indicates that the acidized well yields were about 3.5 times greater. These operations for the Middle Trinity aquifer were reported to have used 1,000 to 15,000 gallons per well of dilute hydrochloric acid.

Within the study area, 287 specific capacity measurements have been reported for the Paleozoic and Cretaceous aquifers. The known duration of these specific capacity measurements varies from five minutes to more than 24 hours. The duration of pumping for some of the measurements is unknown. However, all measurements were considered and included in the number and percent distribution evaluation by aquifer provided in Table 6.

The "Weighted Average Specific Capacities" calculated and shown for the Paleozoic and Cretaceous aquifers in Table 6 indicate the aquifers having the most and least productive wells. The Paleozoic aquifers in order of most to least productivity by well specific capacity are the Ellenburger-San Saba (12.9 gpm/ft) and Hickory (7.7 gpm/ft). Mid-Cambrian and Marble Falls aquifer wells are not represented because a sufficient number of specific capacity measurements are not available for such wells. The Cretaceous aquifers in order of most to least productivity by well specific capacity are the Lower Trinity (4.4 gpm/ft), Middle Trinity (4.2 gpm/ft), Upper Trinity (2.2 gpm/ft), and Edwards Plateau (0.5 gpm/ft). Some of the specific capacity measurements used in the above tabulation for Lower Trinity and Middle Trinity aquifer wells are post-acidized specific capacity measurements.

The longer the duration of pumping time used for specific capacity determination, the more accurate and meaningful the measurement will be to evaluate the long-term performance of a well or group of wells. Table 7 provides the distribution of 114 selected specific capacity measurements (by aquifer) made after two or more hours of pumping time. Some of the selected specific capacity measurements provided in Table 7 for Lower Trinity and Middle Trinity aquifer wells are post-acidized specific capacity measurements. The information presented in Table 7 generally indicates the most and least productive wells by aquifer in the study area.

The specific capacities of wells when properly planned and accurately measured also may be used to determine the following: (1) The projected well specific capacity and drawdown for various assumed well discharge rates (gpm); (2) The operating efficiency and longevity of a well on a long-term basis; (3) The results of enhancement of well performance and productivity due to well reconstruction, deepening and/or treatment (such as acidizing); (4) The number of wells needed to meet current and projected water supply needs under known aquifer conditions; and (5) Under certain known conditions, an estimate of the transmissibility of the aquifer.

Historically, the enhancement or increase of well specific capacity by acidizing apparently has been accomplished successfully in Lower and Middle Trinity aquifer wells. Information on three public supply wells completed in the Lower Trinity aquifer in Kerr County showed that post-acidized specific capacities of the wells were 3.1 to 8.9 times greater than the pre-acidized specific capacities. Approximately 2,000 to 15,000 gallons per well of dilute hydrochloric acid were used during these acidizing operations. Comparison of specific capacities for acidized and non-acidized Lower Trinity aquifer wells in Bandera County indicates that the acidized wells had specific capacities which may have been about 8.6 to 10.3 times greater than the specific capacities of the non-acidized wells. A similar comparison for Middle Trinity aquifer wells in Kerr County indicates that acidized specific capacities may have been about 4.6 to 5.6 times greater.

Table 6. Approximate Distribution of Well Specific Capacities Without Duration Time Considered

Distribution by Specific Capacity Catagories (gpm/ft) By Number (No.) and Percent (%)

Aquifer	Number of Specific Capacities (No./%)	0.9 or Less gpm/ft (No./%)	1.0 to 4.9 gpm/ft (No./%)	5.0 to 19.9 gpm/ft (No./%)	20.0 or more gpm/ft (No./%)	Maximum Specific Capacity (gpm/ft)	Weighted Average Specific Capacity (gpm/ft)	Percent That Is Weighted Average or Greater	Percent Greater Than 0.9gpm/ft
Hickory	6/100	1/17	4/66	0/0	1/17	35.9	7.7	17	83
Elenburger-San Saba	27/100	9/33	9/33	4/15	5/19	85.0	12.9	19	67
Lower Trinity	47/100	25/53	11/24	8/17	3/6	30.2	4.4	26	47
Middle Trinity	177/100	101/57	49/28	22/12	5/3	107.1	4.2	17	43
Upper Trinity	21/100	15/72	3/14	3/14	0/0	16.0	2.2	14	28
Edwards Plateau	9/100	7/78	2/22	0/0	0/0	3.0	0.5	33	22

Table 7. Approximate Distribution of Well Specific Capacities Having a Duration Time of Two Hours or More

Distribution by Specific Capacity Catagories (gpm/ft) By Number (No.) and Percent (%)

Aquifer	Number of Specific Capacities (No./%)	0.9 or Less gpm/ft (No./%)	1.0 to 4.9 gpm/ft (No./%)	5.0 to 19.9 gpm/ft (No./%)	20.0 or more gpm/ft (No./%)	Maximum Specific Capacity (gpm/ft)	Weighted Average Specific Capacity (gpm/ft)	Percent That Is Weighted Average or Greater	Percent Greater Than 0.9gpm/ft
Hickory	4/100	1/25	2/50	0/0	1/25	0.2-35.9	4.0	25	75
Ellenburger-San Saba	15/100	0/0	7/46	4/27	4/27	1.5-51.1	14.1	27	100
Lower Trinity	22/100	11/50	5/23	4/18	2/9	0.1-30.2	5.3	27	50
Middle Trinity	57/100	28/49	18/32	9/16	2/3	<0.1-107.1	5.2	19	51
Upper Trinity	10/100	8/80	2/20	0/0	0/0	<0.1-2.5	0.4	30	20
Edwards Plateau	6/100	5/83	1/17	0/0	0/0	<0.1-3.0	0.4	17	17

The increase of well yield and specific capacity by acidizing of Paleozoic aquifer wells has not been knowingly practiced in the study area. However, since the Ellenburger-San Saba and the Marble Falls aquifers are contained in carbonate rocks, it would seem feasible that under certain conditions acidizing of wells in these aquifers may increase well yields and specific capacities.

Since the water-bearing rock of the Hickory sandstone is usually cemented with siliceous material, it is not possible to readily increase well yield and specific capacity by acidizing. However, some water-bearing Hickory sandstone having carbonate cement may be encountered locally, and may be effectively acidized with dilute hydrochloric acid. Significant portions of the water-bearing rocks of the Mid-Cambrian aquifer (Welge and Lion Mountain sandstones) have quartz and siliceous (glauconitic) sand grains cemented with calcium carbonate. Under these conditions Mid-Cambrian aquifer well yield and specific capacity may be increased effectively by acidizing with dilute hydrochloric acid.

The enhancement of Hickory aquifer well yields and specific capacities by controlled downhole blasting may have been accomplished successfully in Mason and McCulloch Counties northwest of the study area. Such downhole blasting only should be done with extreme caution and by qualified and experienced personnel.

Apparent success has been achieved by using carbon dioxide as an injection fluid to enhance water well production. This method of well development has been used to increase oil and gas well production, and uses the three forms of carbon dioxide (vapor, liquid and solid) as the injection fluid which is injected under pressure into the well bore and water-bearing formation. After the well is pressurized for a period of time, the pressure is released and the carbon dioxide and water flows from the well. This process through agitation and chemical reaction removes drilling mud and other foreign material from the well bore and water-bearing formation, and thus increases well productivity.

The enhancement and longevity of well yield and specific capacity can be achieved by proper gravel packing of wells during their construction. Only a very few large-capacity wells in the study area were reported to have been constructed using the gravel-pack method. Proper gravel packing along with the related proper means of well completion and development can prevent the production of excessive sand and other finer material which readily damages well pumps, and can prevent the plugging of the well by such sand and finer material. Proper gravel packing and related well completion and development should be used for the construction of future large-capacity wells to be completed in the incompetent unconsolidated or semi-consolidated water-bearing sands and sandstones expected or encountered in the Hickory, Mid-Cambrian, and Trinity Group aquifers.

Construction of Wells

The methods used for the construction of water wells are very important in light of the demand for more efficiently productive wells and for the assurance and protection of acceptable ground-water quality provided by the wells on a long-term basis. The six basic types of well construction historically used in the study area are shown in Figure 10. These basic types of well construction were determined by the evaluation of the well records presented in Reeves and Lee (1962), Mount (1963), Reeves (1969), Follett (1973), Walker (1979), Ashworth (1983), and Brune and Duffin (1983), and by the evaluation of more recent well data in the files of the Texas Water Development Board.

A few of the oldest recorded, shallow wells completed in the outcrops of the Paleozoic aquifers used the type of well construction diagramed as Well I on Figure 10. Some of these shallow dug wells were reported to have only "open end" completion where the "Total Depth" of the well was at the bottom of the sealed rock or brick lining. These dug wells have large diameters ranging from 3 to 6 feet, and are now rarely completed and used because of potential sanitary hazards.

The most common types of basic well construction that have been used to drill and complete wells in the Paleozoic aquifers are Wells II and III in Figure 10. The diameters of the well casings in rural domestic and/or livestock watering wells range from 4 to 8 inches. Public supply and irrigation wells constructed like Well II commonly have casing diameters of 7 to 10 inches. Large-capacity wells constructed and used for public supply purposes, and having construction like Well III have used large casings with diameters of 10 to 16 inches and smaller casings with diameters of 7 to 12 inches. The open hole type of completion of Wells II and III can be effectively used in most Paleozoic aquifer wells because the aquifers are composed of very competent, consolidated carbonate rocks and sandstones. However tests conducted in Gillespie County on a large-capacity Hickory well with open hole completion similar to Well II indicated the production of an undesirable amount of sand during a desired high yield. To avoid this undesirable production of sand, the well could have been initially constructed, or re-constructed, like Wells IV or V and properly gravel packed to obtain the desired higher yield.

One Hickory well used for public supply purposes in Gillespie County was reported to have the type of construction similar to Well VI in Figure 10. The annulus portion of the well indicated by the asterisk (*) was reported to have been gravel packed. This is one of the very few wells in the entire study area reported to have been gravel packed during its construction. The similar annulus areas for Wells IV and V, which are marked with asterisks (*), could be considered for effective gravel packing, if such construction is determined to be needed to provide a desired higher well yield. As indicated previously, proper gravel packing of large-capacity Hickory and perhaps Mid-Cambrian wells constructed like Wells IV, V and VI can avoid the production of undesirable amounts of sand and provide much higher well yields and specific capacities on a long-term basis.

The Cretaceous aquifer wells are constructed similar to Wells I through VI in Figure 10. A few shallow dug wells like Well I are found completed in the outcrop areas of the Upper Trinity and Middle Trinity aquifers. These dug wells have diameters of 2 to 5 feet. The most common type of well construction used for Cretaceous aquifer, rural domestic and/or livestock watering wells is Well II. Usually these wells have casing diameters of 4 to 8 inches. If caving of shale and clay is expected, wells similar to Wells III, IV and V are drilled and completed.

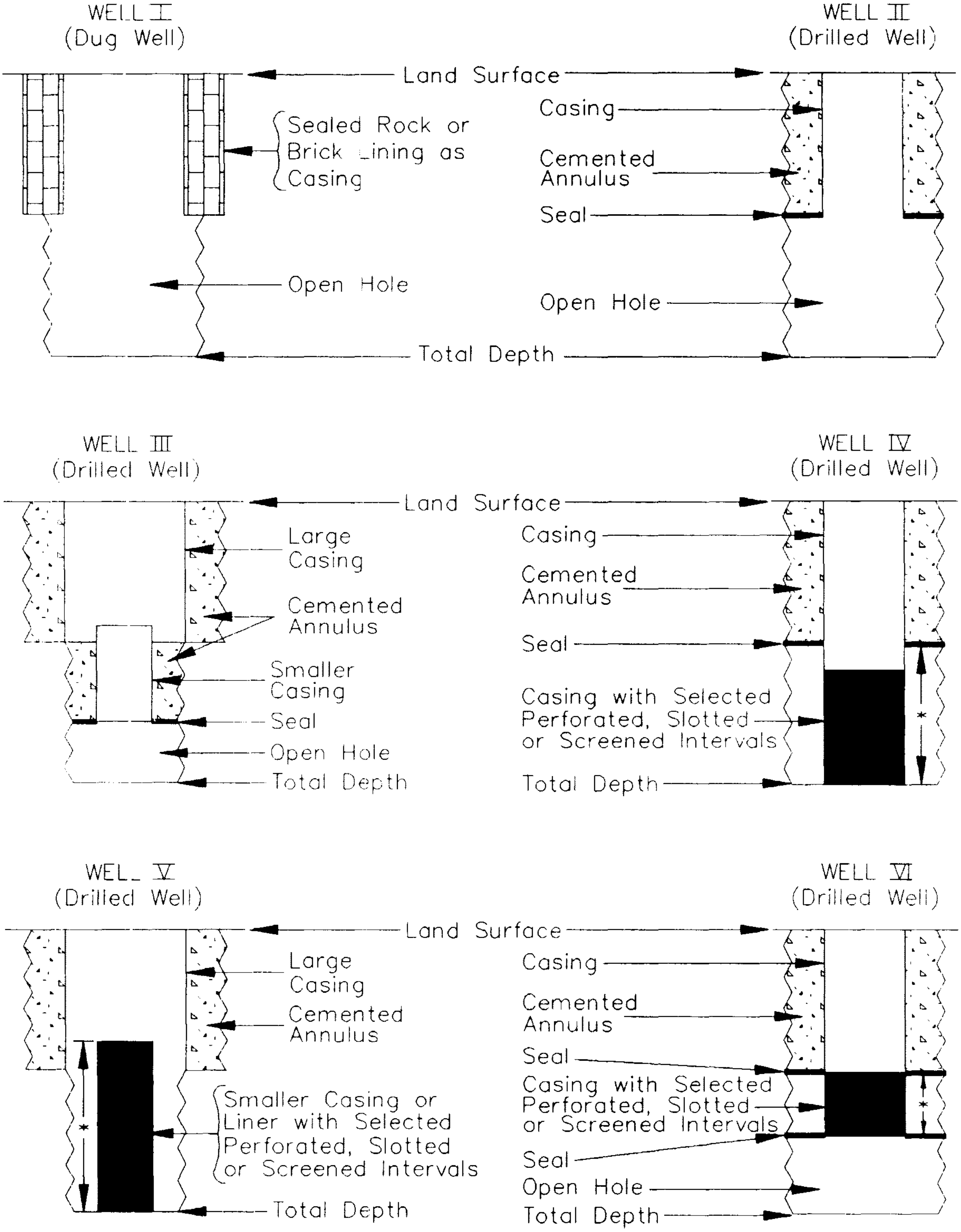


Figure 10

DIAGRAMS SHOWING BASIC TYPES OF WELL CONSTRUCTION

About 95 percent of the existing wells that are completed in the Edwards Plateau aquifer in Bandera, Gillespie, and Kerr Counties are completed open hole in a manner similar to Well II in Figure 10. Most of these wells have casing diameters of 6 or 7 inches. About 75 percent of these wells were completed before 1950, and about 65 percent have the casing set at a depth of less than 10 feet (Reeves and Lee, 1962; Reeves, 1969; and Walker, 1979). Most of these wells probably do not have the casing properly cemented to provide an adequate seal from potential surface and shallow subsurface sanitary hazards.

Most of the wells completed in the Upper Trinity aquifer have construction similar to Well II in Figure 10, commonly have casing diameters of 6 to 8 inches, and are used for rural domestic and livestock watering purposes. The major well construction consideration for Upper Trinity aquifer wells is the amount (length) of casing that needs to be set and the proper cementing of such casing in the borehole. In most of the study area, the Upper Trinity aquifer has highly mineralized water commonly found in two evaporite zones. When completing wells, these zones need to be cased-off and the casing properly cemented.

Wells similar to Wells II, III, IV and V in Figure 10 are usually constructed as Middle Trinity aquifer wells for municipal and industrial water supply purposes. These wells most commonly have minimum casing diameters of 4 inches and maximum casing diameters of 12 inches. It is very important that Middle Trinity aquifer wells have properly set and cemented casings to avoid production of any highly mineralized water that may be encountered in the overlying evaporite zones of the Upper Trinity aquifer.

Lower Trinity aquifer wells in Kerr, Kendall, and Bandera Counties are constructed with open hole completion like Wells II and III in Figure 10. The Sligo and Hosston members of the Travis Peak Formation (Table 1) in these areas are sufficiently competent and consolidated so that high well yield with open hole completion can be achieved. The casings in these wells need to be set and cemented to a depth below the base of the Hammett member to avoid caving from the Hammett and other overlying incompetent and unconsolidated strata, and to avoid production of water from the evaporite zones of the Upper Trinity aquifer. Those wells for public supply purposes usually have large casing diameters of 16 to 20 inches and smaller casing diameters of 8 to 12 inches. The Hosston member in Hays and Travis Counties is usually found to be incompetent and in part unconsolidated. In these areas, wells are constructed similar to Wells IV and V with large casing diameters of 10 to 12 inches and smaller casing diameters of 6 to 8 inches.

Well VI in Figure 10 illustrates well construction commonly used to produce water from both the Middle Trinity aquifer and the Lower Trinity aquifer. The casing with selected perforated, slotted, or screened intervals is set opposite the Middle Trinity aquifer, while the open hole interval is positioned opposite the competent and consolidated water-bearing rocks of the Lower Trinity aquifer (Sligo and Hosston members). The lower seal is required to prevent filling of the open hole portion of the well by incompetent rock material from the Hammett member. The casing above the perforated, slotted or screened intervals opposite the Middle Trinity aquifer should be properly cemented to prevent production of water from the evaporite zones of the Upper Trinity aquifer.

The dark shaded casing or liner shown on Wells IV, V, and VI in Figure 10 indicates that portion of the well open to the aquifer. These dark shaded portions of casing or liner may be selectively perforated, slotted or screened at two or more depth intervals within specific selected portions of its entire length, or may be perforated, slotted, or screened within one continuous depth interval throughout most of its entire length. Only a very few of these type of wells which have been completed in the Cretaceous aquifers were reported to be gravel packed. Such gravel packing could be accomplished in these wells by placing gravel in the annulus areas marked with an asterisks (*). Since these types of well construction are used in those portions of the Trinity Group aquifers which are expected to have very fine grained, incompetent and unconsolidated deposits, a properly sized, sorted and installed gravel pack should be considered as a means to enhance well productivity and longevity.

Wells II through VI shown in Figure 10 should be properly cemented using gravity and/or pressure cementing methods and procedures. Proper cementing of a well provides reasonable assurance that undesirable waters from various adjacent surface and subsurface sources will not enter the well and contaminate the ground-water discharged by the well. The casings, liners and screens used in the construction of wells should be made of material that will be reasonably resistant to corrosion and avoid mechanical failures. Most wells in the study area use steel casings and liners or metal screens in wells constructed similar to Wells IV, V, and VI in Figure 10. The main advantage in the use of metal casings, liners and screens is that they provide great strength and durability; especially during the cementing phase of well construction in the deeper wells. Plastic casings, liners, and screens may be used to construct wells, but caution should be used during their installation. The use of plastic materials should be limited according to some specific well depth, because plastic well materials are not as strong as metal materials. Also certain plastic casings that are intended to be cemented are known to become distorted and buckle during and soon after the cementing phase of well construction. It has been reported that certain plastic casings will develop such a problem due to the heat generated by certain types of cement during the placement and curing of the cement in the well bore annulus. Compatible plastic casing and cements should be used to avoid this problem.

Well drillers, well operators, and well owners should use and practice the principles, methods, and procedures described for well design, construction, and operation provided in Driscoll (1986). Those persons or entities needing a well drilled should use a water well driller registered with the Texas Water Commission.

Water-Level Changes

Under natural conditions without withdrawals by wells, water-level changes in an aquifer are caused by the changes of the natural recharge-discharge conditions of the aquifer. When the amounts of natural recharge and natural discharge are the same and balanced, water-level changes in the aquifer are essentially negligeable. However, when natural recharge is reduced during dry periods, water is discharged naturally from transit storage and water levels decline accordingly. When the aquifer again is replenished by adequate rainfall, the volume of water drained from transit storage is replaced and water levels will rise accordingly. Withdrawals by wells disrupt this natural condition and artificially cause various water-level changes. Coupled with the natural changes of recharge-discharge conditions described above, the amount and extent of water-level changes depend on the frequency, amount, and distribution of the withdrawals by wells, and the amount and distribution of the aquifer's coefficients of transmissibility and storage which control the flow and availability of water to replenish the withdrawals by wells. Mount (1963) appropriately describes these and other conditions which cause water-level changes.

Very few water-level observation wells were available to this study to evaluate the net changes in water-levels in the Paleozoic aquifers. Those net water-level changes detected or estimated for the Hickory, Ellenburger-San Saba and Marble Falls aquifers for the 1977-1987 period are shown on Figure 11 which also provides the elevation of the water-level in 1987. Maximum net water-level declines detected or estimated for the 1977-1987 period were about 19 feet in the Hickory aquifer (north of Fredericksburg, north-central Gillespie County), about 32 feet in the Ellenburger-San Saba aquifer (southeast of Johnson City, central Blanco County), and about 6 feet in the Marble Falls aquifer (near Cypress Mill, eastern Blanco County). Long-term net water-level declines detected in the Hickory and Ellenburger-San Saba aquifers are provided in Table 8.

A significant amount of data is available to evaluate the net water-level changes from 1977 to 1987 in the Trinity Group aquifers within the study area. Those net water-level changes detected or estimated for the Lower Trinity aquifer for the 1977-1987 period are shown on Figure 11. Those 1977-1987 net water-level changes for the Middle and Upper Trinity aquifers are shown on Figure 12. Figures 11 and 12 provided the elevations of the water-levels of the Lower, Middle and Upper Trinity aquifers in 1987. Sufficient water-level data was available to approximately contour the elevation of the 1987 water-level of the Middle Trinity aquifer as shown on Figure 12. A summary of the approximate net water-level changes in the Trinity Group aquifers from 1977 to 1987 is provided in Table 9. The approximate statistical distribution of these 1977-1987 net water-level changes in the Trinity Group aquifers by rise and decline range catagories is given in Table 10.

Maximum net water-level declines detected or estimated for the 1977-1987 period were about 155 feet in the Lower Trinity aquifer (at Bandera, Bandera County), about 59 feet in the Middle Trinity aquifer (near Comfort in eastern Kerr County), and about 16 feet in the Upper Trinity aquifer (southwest of Bandera, Bandera County). Although net water-level rises occurred in some parts of the study area during the 1977-1987 period, net water-level declines in the Trinity Group aquifers significantly out-weighted net water-level rises in both areal distribution (Figures 11 and 12) and statistical distribution (Table 10). The most significant, long-term, net water-level changes detected or estimated for the Trinity Group aquifers are provided in Table 11.

Very few water-level measurements in observation wells completed in the Edwards Plateau aquifer were available to this study. The elevation of the 1987 water levels and the net changes in the water levels of the aquifer from 1977 to 1987 are shown for four wells on Figure 12 in Bandera and Kerr Counties. Measurements and estimates of water levels in two wells indicated net water-level rises, while measurements and estimates in two other wells indicated net water-level declines.

To gain a visual perspective on the water-level changes detected and estimated in the Paleozoic and Cretaceous aquifers, the reader is referred to Figures 13 through 18. These illustrations show hydrographs for the water levels measured and estimated in selected water-level observation wells completed in the Paleozoic and Cretaceous aquifers. Water-level measurements from observation wells were not available for such illustrations for Comal and Medina Counties.

The significant long-term water-level declines that have been detected in the Hickory and Ellenburger-San Saba aquifers were mainly caused by concentrated ground-water withdrawals coupled with deficient transmissibilities of the aquifers. Lack of saturated sand thickness and probably barriers due to faulting have caused water-level declines in the Hickory aquifer. Deficient transmissibility due to lack of extensive lateral and vertical development of solution openings have caused water-level declines in the Ellenburger-San Saba aquifer.

Concentrated ground-water withdrawals coupled with deficient transmissibility are the cause of the greater long-term water-level declines that have been detected in the Trinity Group aquifers, particularly in the Lower and Middle Trinity aquifers. The amount and distribution of transmissibilities of the Lower Trinity aquifer especially are highly variable, ranging from as high as 15,000 to 25,000 gpd/ft in Kerr and Bandera Counties to as low as 140 to 1,900 gpd/ft in Travis County (Ashworth, 1983, Brune and Duffin, 1983, and Guyton, 1973). The moderate to extremely low transmissibilities of the Paleozoic and Cretaceous aquifers make it extremely difficult to economically develop and use the relatively large ground-water reserves without adverse long-term water-level declines in and near centers of concentrated pumpage.

Table 8.-Approximate Long-Term Net Water-Level Declines in the Hickory and Ellenburger-San Saba Aquifers

Aquifer	Location and Explanation As Needed	Period (Years)	Approximate Net Water-Level Change Decline (Feet)	Approximate Net Water-Level Change Rate of Decline (Feet/Year)
Hickory	Northwestern Blanco County Well 57-37-402 west of Round Mountain	1968-1987	2.7	0.1
Ellenburger-San Saba	Central Blanco County Well 57-45-903 just east of Johnson City	1938-1984	5.6	0.1
Hickory	North-Central Gillespie County Well 57-41-301, City of Fredericksburg Well	1962-1985	51	2.2
Hickory	North-Central Gillespie County Well 57-42-101 near City of Fredericksburg Well	1953-1987	108	3.2
Ellenburger-San Saba	South-Central Gillespie County Wells 57-50-102 and 104 in the City of Fredericksburg's Pedernales River Well Field	1939-1986	26	0.6

Table 9. Summary of Approximate Net Water–Level Changes in theTrinity Group Aquifers, 1977-1987

Aquifer	Number of Observations	1977-1987 Range in Net Change Observed Rise (+) Decline (-)	1977-1987 Average Net Change Rise (+) Decline (-)	Percent Average or Greater	Ratio of Rises to Declines
Lower Trinity	14	+155 to -155	-5.3	64	1 to 3.7
Middle Trinity	45	+30 to -59	-8.2	33	1 to 1.5
Upper Trinity	5	+8 to -16	-3.8	40	1 to 4.0
Trinity Group	64	+155 to -155	-7.2	42	1 to 1.9

Table 10. Approximate Distributions of Net Water-Level Changes in the Trinity Group Aquifers, 1977-1987

	Rise	Range	Categories	in Feet	No Change	Decline	Range	Categories in Feet	
	>25.0	10-0-25.0	2.0-9.9	0.1-1.9	Zero	0.1-1.9	2.0-7.1	7.2-25.0	>25.0
Number of Observations	4	5	9	4	0	4	11	16	11
	Total-22					Total-42			
Approximate Percent	6.2	7.8	14.1	6.2	0	6.2	17.2	25.1	17.2
	Total-34.3%					Total-65.7%			

Table 11.–Approximate Long-Term Net Water-Level Changes in the Trinity Group Aquifers

Aquifer	Location/Explanation As Needed	Period (Years)	Approximate Net Water-Level Change	
			Decline(-), Rise(+) (Feet)	Rate of Change (Feet/Year)
Lower Trinity	Bandera County Well 69-24-202 in City of Bandera	1953-1987	-271	-8.0
Lower Trinity	Bandera County Well 69-24-102 in City of Bandera	1967-1987	-157	-7.9
Middle Trinity	Bandera County Well 69-24-203 in City of Bandera	1954-1984	-84	-2.8
Middle Trinity and Hickory	Gillespie County Well 57-41-901 in City of Fredericksburg National Guard Well Field	1962-1983	-105	-5.0
Middle Trinity	Hays County Well 57-56-702 near City of Dripping Springs	1975-1986	-108	-9.8
Middle Trinity	Hays County Well 57-64-702 near City of Wimberly	1974-1987	-2.4	-0.2
Middle Trinity	Kendall County Wells 68-01-301 and 68-01-303 in City of Comfort	1947-1987	-98	-2.5
Middle Trinity	Kendall County Wells 68-02-301 and 68-01-310 in City of Comfort	1947-1987	-84	-2.1
Middle Trinity	Kendall County Well 68-01-303 in City of Comfort	1957-1987	-53	-1.8
Middle Trinity	Kendall County Wells 68-11-701 and 68-11-708	1940-1978[1]	-102	-2.7
	in City of Boerne 1-Before surface water was used.	1978-1987[2]	+1	+0.1
	2-After surface water was used.	1940-1987	-101	-2.1
Middle Trinity	Kendall County Wells 68-11-412 and 68-11-715	1956-1979[1]	-12	-0.5
	in City of Boerne 1-Before surface water was used.	1979-1988[2]	+26	+2.9
	2-After surface water was used.	1956-1988	+14	+0.4

continued

Table 11.–Approximate Long-Term Net Water-Level Changes in the Trinity Group Aquifers *(cont'd.)*

			Approximate Net Water-Level Change	
Aquifer	**Location/Explanation As Needed**	**Period (Years)**	**Decline(-), Rise(+) (Feet)**	**Rate of Change (Feet/Year)**
Middle Trinity	Central Kendall County Well 68-11-103 north of Boerne	1965-1986	-7.9	-0.4
Lower Trinity	Eastern Kendall County Well 68-04-909 south of Kendalia near Guadalupe River	1965-1987	-12.7	-.06
Lower Trinity	City of Kerrville Wells 56-63-601, 603, and	1923-1980[1]	-319	-5.6
	604 from City Water Level Records	1980-1987[2]	+111	+15.9
	[1]Before large scale surface water use [2]After large scale surface water use	1923-1987	-208	-3.3
Lower Trinity	City of Kerrville Well 56-63-608	1952-1976[1]	-60	-2.5
	[1]Before large scale surface water use	1976-1987[2]	+26	+2.4
	[2]After large scale surface water use	1952-1987	-34	-1.0
Middle Trinity	Eastern Kerr County Well 57-57-703 northwest of Comfort	1967-1987	-26.4	-1.3
Middle Trinity	Eastern Kerr County Well 68-01-505 southwest of Comfort	1974-1987	-52.0	-4.0
Middle Trinity	Southeastern Kerr County Well 69-16-201 between Center Point and Bandera	1959-1987	-58.9	-2.1
Lower Trinity	Western Travis County Well 58-33-403 southeast of Lago Vista	1967-1987	-49.6	-2.5
Lower Trinity	Western Travis County Well 58-41-101 northwest of Bee Cave	1971-1988	-12.7	-0.7
Lower Trinity	Travis County Well 58-42-502 at St. Stephens School northwest of Austin	1949-1986	-154	-4.2

CHEMICAL QUALITY OF GROUND WATER

The chemical constituents in ground water are dissolved from the soils and rocks as water percolates from the land surface through the unsaturated zone and into the saturated zone of an aquifer. Rainfall is relatively free of minerals but is inherently slightly to moderately acidic (pH less than 7.0) which makes it a very effective solvent. As water slowly percolates downward under the influence of gravity to and through an aquifer, it dissolves some of the minerals in the soil and rocks at a relatively consistent rate and in an accumulative manner. Also, as the water percolates to and through an aquifer, it may encounter pollutants introduced by the activities of man on and beneath the land surface. When pollutants are encountered, they become at various concentrations part of the water-quality regime of the aquifer, and alter the natural or ambient chemical character of the ground water. Other important factors that influence the mineralization of ground water are the length of time the water has been in contact with the rocks and any pollutants, the solubility of the minerals and pollutants in the soils and rocks, the amount of carbon dioxide dissolved in the percolating water, the variances in the permeabilities of the soils and rocks, any structural geological features (such as faults) which impede the flow of the percolating waters, and the subsurface temperature and pressure which inherently increase with the increase in depth below the land surface.

The results of more than 5,800 ground-water chemical analyses for the eight aquifers within the study area were examined. Because of the very large amount of data available, only eleven important chemical constituents and characteristics were selected and considered for evaluation and description. They include nitrate, fluoride, chloride, sulfate, dissolved solids, sodium, hardness, iron, alpha radiation, and radium. In all, about 5,784 individual analysis were used, and included 876 for nitrate, 856 for fluoride, 774 for chloride, 991 for sulfate, 732 for dissolved solids, 724 for sodium, 759 for hardness as $CaCO_3$, 41 for iron, 24 for alpha radiation, and 7 for radium. The abundance, sources, form of occurrence, concentration, significance and maximum constituent level(s) for each of these selected constituents and characteristics and other important constituents and properties of water are presented in Appendix A (Texas Water Development Board, 1989c).

Figure 19 provides the concentrations of sulfate, chloride and total dissolved solids contents in the water from selected wells and springs producing from the water-bearing units of the Paleozoic and Trinity Group aquifers (modified from Ashworth, 1983). Such information on water quality for the Edwards Plateau aquifer is provided in Walker (1979).

A water-quality summary for each aquifer addressing the concentrations of nitrate, fluoride, chloride, sulfate, dissolved solids, sodium and hardness as $CaCO_3$ is presented in Appendix B. These summaries do not include iron, alpha radiation, and radium because only a very limited number of analyses were available for these constituents. In addition, detailed evaluations were made:

1) to determine the statistical and areal (by county) distribution of nitrate, fluoride and sulfate concentrations detected in each of the eight aquifers, using the most recent analyses made during the historical period from the late 1930's to the mid 1980's, and
2) to determine the changes in nitrate concentrations detected in each aquifer during the historical period from the late 1930's to the mid-1980's.

Information on the distribution in the concentrations of nitrate, fluoride and sulfate was compiled for each aquifer as provided respectively in Appendices C-1, C-2 and C-3. These specific constituents were addressed because of the abundance of analyses available for these constituents and because of their importance as significant indicators to determine if a ground-water source has water-quality problems and if it is capable of meeting primary and secondary drinking water standards (Texas Department of Health, 1988b).

An unusually or excessively high concentration of nitrate, above the approximate ambient level concentration for a specific aquifer, is a significant and reasonably reliable indicator of pollution from human or animal wastes and/or ranching and farming activities. Unusually or excessively high concentrations of nitrate in ground water can be caused by the dissolution of nitrate minerals which may exist naturally in the rocks within or adjacent to the aquifer. Not any of the geological units are known to have high concentrations of such nitrate minerals within the study area. However, nitrate mineral deposits have been found in faulted and fractured rocks of the Ellenburger Group in San Saba County north of the Llano uplift.

Figures 20, 21 and 22 provide visual distributions of these detected historical nitrate concentrations by range in concentration catagories for each of the eight aquifers. The nitrate range in concentration category symbols used on these maps are intended to provide a visual perspective on where and to what degree each aquifer has nitrate pollution within the study area. Such pollution is readily indicated locally for certain urbanized areas for the Trinity Group aquifers and some of the Paleozoic aquifers (Figures 20, 21 and 22). Also, it is very apparent that the Edwards Plateau aquifer has widespread nitrate pollution in the rural portion of western Gillespie County and northwestern Bandera County (Figure 21). Similar, but more local, rural nitrate pollution of some of the Paleozoic aquifers in Blanco and Gillespie Counties is indicated on Figure 20.

Table 12 which was prepared from information in Appendix C-1 is a summary of the percent distributions of nitrate concentrations by aquifer. A numerical rating of these nitrate concentration distributions by aquifer provides an approximate indicator of the apparent most and least nitrate pollution by aquifer. In the order of most to least nitrate pollution, the aquifers are rated as follows:

Marble Falls Aquifer - Has very serious nitrate pollution in the Cypress Mill area of eastern Blanco County. Similar nitrate pollution is also apparent in the Honeycut Bend area east of Johnson City in eastern Blanco County (Figure 20).

Table 12. Summary of Percent Distributions of Nitrate Concentrations by Aquifer

Aquifer	Percent Distributions Exceed MCL of 44.3 mg/l	Exceed Regional Average of 10.6 mg/l	Exceed Ambient Level of 1.0 mg/l
Hickory	2.9%	14.3%	45.7%
Mid-Cambrian	9.7%	41.9%	77.4%
Ellenburger-San Saba	5.4%	37.8%	78.4%
Marble Falls	27.3%	90.9%	100.0%
Lower Trinity	2.3%	9.1%	34.1%
Middle Trinity	2.8%	12.1%	42.6%
Upper Trinity	2.2%	9.6%	53.3%
Edwards Plateau	9.5%	312.4%	73.3%

Mid-Cambrian Aquifer - Serious nitrate pollution detected in rural area west-northwest of Round Mountain in northern Blanco County and in a rural area north of the Pedernales River and west of U.S. Highway 281 in west-central Blanco County (Figure 20).

Ellenburger-San Saba Aquifer - Has moderate nitrate pollution detected along Pedernales River from U.S. Highway 290 bridge southeast of Fredericksburg in Gillespie County to Johnson City in Blanco County. Serious nitrate pollution is evident at Johnson City in Blanco County (Figure 20).

Edwards Plateau Aquifer - Has serious nitrate pollution in widespread rural area of western and central Gillespie County; particularly in area north of U.S. Highway 290. Similar nitrate pollution is indicated in a rural area of northwest Bandera County (Figure 21).

Hickory Aquifer - Has serious nitrate pollution in a local area adjacent to FM Highway 1323 in northwest Blanco County. Moderate nitrate pollution is evident in local areas north of Fredericksburg between U.S. Highway 87 and State Highway 16 (Figure 20).

Middle Trinity Aquifer - Has serious to moderate nitrate pollution in urbanized areas at and near Comfort (Kendall and Kerr Counties), Blanco (Blanco County), Kendalia (Kendall County), Berghiem (Kendall County), and Boerne (Kendall County). Also, has serious nitrate pollution in local rural areas of Gillespie and Blanco Counties (Figure 22).

Upper Trinity Aquifer - Most serious nitrate pollution in local rural areas of northern Kendall and northern Hays Counties. Moderate pollution found in urbanized area at and near Blanco (Blanco County) and Dripping Springs (Hays County). Also, moderate pollution found in urbanized area just north of U.S. Highway 290 between State Highway 71 and Travis-Hays County line in southwest Travis County (Figure 21).

Lower Trinity Aquifer - Serious nitrate pollution found in generally urbanized area along Pedernales River arm of Lake Travis in western Travis County (Figure 21).

Most of the nitrate pollution described above has occurred in those portions of the respective aquifers nearest to the land surface. The nitrate pollution in urbanized areas probably is attributed to septic tank discharges, while the nitrate pollution in rural areas probably is attributed to animal waste and/or septic tank discharges. Livestock and other animal wastes probably are the main cause for the widespread nitrate pollution of the Edwards Plateau aquifer detected in western Gillespie County and northwest Bandera County (Figure 21). Other animal wastes may include excrements produced by wildlife on the land surface and by bats in caves which occur in the carbonate rocks above the zone of saturation of the Edwards Plateau aquifer.

Changes in nitrate concentrations in the ground waters from one year to another for the historical period from the late 1930's to mid-1980's was evaluated for 162 wells. Available data indicate a general decrease in nitrate concentrations in the ground water analyses evaluated for the Paleozoic and Trinity Group aquifers. Of the 20 Paleozoic wells sampled during various time periods, three wells or 15 percent had significant increases in nitrate concentration, 16 wells or 80 percent had significant decreases and one well or about 5 percent had no change. Of the 124 Trinity Group aquifer wells sampled during various time periods, 33 wells or 27 percent had significant increases in nitrate concentration, 79 wells or 64 percent had significant decreases and 12 wells or 9 percent had no change. The Edwards Plateau aquifer which has widespread nitrate pollution had very significant increases in nitrate concentrations during various periods from the late 1930's to the mid-1980's. Of the 18 Edwards Plateau aquifer wells sampled, 16 wells or 89 percent had significant increases in nitrate concentration and two wells or 11 percent had decreases. These results are somewhat suspect, because the accuracies of the methods and procedures used for sampling and analyzing waters for nitrate changed considerably during the 1930's to mid-1980's period.

Information on the concentrations of fluoride in the ground waters of the eight aquifers in the study area is provided by aquifer in the water quality summaries in Appendix B. Appendix C-2 provides the distribution of fluoride concentrations by range in concentration catagories, averages and medians by county for each of the eight aquifers.

The unusually high to excessive concentrations of fluoride detected in the ground waters of the Trinity Group aquifers (Appendix C-2) are present due to the dissolution of naturally occurring fluoride minerals within some of the sedimentary rocks of the Trinity Group. Such unusually high to excessive concentrations of fluoride are readily detected in the deeper portions of the Trinity Group aquifers; particularly in the Lower Trinity aquifer in Travis and Bandera Counties, the Middle Trinity aquifer in Travis, Hays, Bandera, Kendall and Kerr Counties, and the Upper Trinity aquifer in Travis, Hays and Bandera Counties. Such inherent concentrations of unusually high to excessive concentrations of fluoride were also detected in the Mid-Cambrian aquifer in Blanco and Gillespie Counties.

The 774 analyses evaluated for chloride concentrations in the eight aquifers indicate that chloride does not pose significant problems in the use of ground waters for public supply, manufacturing and irrigation purposes. Information on the concentrations of chloride in the ground waters of the study area is provided in Appendix B. The concentrations of chloride detected in the ground waters from selected wells and springs producing from the various water-bearing rocks of the Paleozoic and Trinity Group aquifers are provided on Figure 19. Such information on chloride in the Edwards Plateau aquifer is provided in Figure 16 in Walker (1979).

Information on the concentrations of sulfate in the ground waters of the eight aquifers is provided by aquifer in the water quality summaries in Appendix B. Appendix C-3 provides the distribution of sulfate concentrations by range in concentration catagories, averages and medians by county for each of the eight aquifers in the study area. The concentrations of sulfate detected in the ground waters from selected wells and springs producing from the various water-bearing rocks of the Paleozoic and Trinity Group aquifers are provided on Figure 19. Such information on sulfate in the Edwards Plateau aquifer is provided on Figure 16 in Walker (1979).

The predominant sulfate minerals found in the sedimentary rocks of the study area are anhydrite and gypsum. Large deposits of these minerals are found as prominent evaporite beds within the upper unit of the Glen Rose Formation (Table 1). Thin layers of gypsum and anhydrite are found in the Cow Creek member of the Travis Peak Formation (Table 1). Most of the other sedimentary rocks of the Trinity Group probably contain very small to moderate amounts of anhydrite and gypsum; particularly the marls, shales and clays of the Glen Rose Formation and the shales and clays of the Travis Peak Formation. The unusually high to excessive concentrations of sulfate detected in the ground waters of the Upper Trinity aquifer (Appendix C-3) are due to the dissolution of the prominent evaporite beds within the upper unit of the Glen Rose Formation. The unusually high to excessive concentrations of sulfate detected in the Middle Trinity aquifer (Appendix C-3) is probably caused by the existence and dissolution of the thin beds of anhydrite and gypsum found in the Cow Creek member of the Travis Peak Formation. Some of the unusually high to excessive concentrations of sulfate detected in the Trinity Group aquifers can be avoided by proper well construction. If the prominent anhydrite and gypsum beds of the upper unit of the Glen Rose Formation and in some cases the thin layers of anhydrite and gypsum of the Cow Creek member are not prevented from supplying ground waters to wells, waters pumped from such wells will contain unusually high to excessive concentrations of sulfate. Also, improperly sealed, cased, and cemented boreholes which pass through the upper unit of the Glen Rose Formation are conduits of high sulfate ground waters which leak downward and readily contaminate the relatively low sulfate waters produced from portions of the Middle Trinity aquifer and/or from the Lower Trinity aquifer.

Most of the excessive concentrations of dissolved solids detected are due to the related high concentration of sulfate; particularly in the Trinity Group aquifers. Dissolved solids is included in the water-quality summary for each aquifer in Appendix B. The concentrations of dissolved solids detected in the ground waters from selected wells and springs producing from the various water-bearing rocks of the Paleozoic and Trinity Group aquifers are provided on Figure 19. Such information on dissolved solids in the Edwards Plateau aquifer is provided on Figure 16 in Walker (1979).

Sodium is included in the water-quality summary for each aquifer in Appendix B, because of its apparent effect on human blood pressure and irrigated soils. Excessive sodium concentrations are believed to cause high blood pressure; consequently, a maximum level concentration of 20 mg/l in drinking water is recommended for most persons having high blood pressure (Lappenbusch, 1988). All of the eight aquifers have ground pressure (Lappenbusch, 1988). All of the eight aquifers have ground waters with an average sodium concentration of 20 mg/l or more. The greatest average concentrations above the 20 mg/l were determined for the Lower Trinity (183 mg/l), the Hickory (60 mg/l), the Middle Trinity (49 mg/l) and the Mid-Cambrian (46 mg/l) aquifers. The highest concentrations of sodium were found generally in the deeper wells completed in these sandstone aquifers. Ground waters with lower average concentrations of sodium at or slightly greater than 20 mg/l were determined to be in the carbonate rocks of the Edwards Plateau (20 mg/l), Marble Falls (21 mg/l), Ellenburger-San Saba (24 mg/l) and Upper Trinity (26 mg/l) aquifers.

A high sodium content has been found to limit the use of water for irrigation because excessive concentrations are known to impair the tilth and permeability of the soil (See "Sodium", "Percent Sodium", "Sodium Adsorption Ratio" and "Residual Sodium Carbonate" in Appendix A). Calculations of the sodium hazard for the ground waters of the Paleozoic and Cretaceous aquifers indicate no significant problems with use of such waters for irrigation of the soils. Only ten deep wells produced waters having a significant sodium hazard. These wells consisted of three deep Hickory wells in Blanco County and seven deep Lower Trinity wells in Bandera (2 wells) and Kendall (5 wells) Counties. A majority of these wells had depths greater than 1,000 feet.

Hardness as $CaCO_3$ is included in the water quality summary for each aquifer in Appendix B. All of the ground waters analyzed are inherently hard to very hard. For more information on the hardness of ground water, please refer to Appendix A.

Only a limited number of historical iron analyses were available. The 41 available analyses had iron concentrations which ranged from 0.0 to 9.9 mg/l with 41 percent exceeding the secondary drinking water standard MCL of 0.3 mg/l for iron, and 24 percent exceeding the average iron concentration of 1.1 mg/l for all ground waters analyzed for iron. The available data and the above evaluation for iron should be considered inconclusive as to whether ground waters in the study area have serious iron problems. Future analyses for iron should be made by using correct water sample collection, treatment and transport methods and procedures to assure that the water sampled will have iron concentrations representative of the waters in the aquifers. Other than natural iron content of the aquifer, high iron concentrations in water may be derived from well casings, pipes, pumps, storage tanks and other cast iron and steel water delivery facilities and equipment.

A very limited number of selected radioactive analyses of the ground waters in the study area were made. Those limited radioactive analyses made include 24 analyses for alpha radiation and 7 analyses for total radium which includes radium-226 plus radium-228.

The results of the limited number of analyses for alpha radiation are as follows:

(1) Six alpha analyses made of Hickory waters in Gillespie County had a range of about 8.4 to 44 picocurries per liter (pCi/l) with an average alpha of 25 pCi/l. Approximately 50 percent of the analyses exceed the average concentration of 25 pCi/l while about 67 percent of the analyses exceed the primary drinking water standard MCL of 15 pCi/l for alpha.

(2) One alpha analysis made of Mid-Cambrian water in Gillespie County had a very high concentration of about 59 pCi/l. This concentration is almost 4 times greater than the MCL of 15 pCi/l for alpha.

(3) Six alpha analyses made of Ellenburger-San Saba waters in Blanco and Gillespie Counties had a range in alpha of less than 2.0 pCi/l to about 4.7 pCi/l with an average concentration of about 2.1 pCi/l.

(4) One alpha analysis made of Marble Falls water in eastern Gillespie County had a concentration of about 4.4 pCi/l.

(5) Three alpha analyses made of Lower Trinity waters in Bandera, Kendall, and Kerr Counties had a range in alpha of less than 2.0 pCi/l to about 5.3 pCi/l with an average concentration of about 3.8 pCi/l.

(6) Seven alpha analyses which were made for Middle Trinity waters in Gillespie (3), Kendall (3), and Kerr (1) Counties had a range in alpha of less than 2.0 pCi/l to about 11 pCi/l with an average concentration of about 4.4 pCi/l. The highest concentration of 11 pCi/l was in water from a Gillespie County well at Fredericksburg which is believed to produce water from both the Middle Trinity aquifer (Hensell sand) and the Hickory aquifer directly underlying the Hensell sand.

The results of the very limited number of analyses for total radium (radium-226 plus radium-228) are as follows:

(1) Two total radium analyses made of Hickory waters in Gillespie County had a range of 16.0 to 18.4 pCi/l with an average concentration of about 17.2 pCi/l. The two analyses were about 3.2 to 3.7 times greater than the MCL of 5.0 pCi/l for total radium.

(2) Two total radium analyses made of Lower Trinity waters in Kendall and Kerr Counties had a range of approximately 4.4 to 6.0 pCi/l with an average concentration of about 5.2 pCi/l. The 6.0 pCi/l concentration was detected in the water from a well in Kendall County at Comfort and exceeds the MCL of 5.0 pCi/l for total radium.

(3) Three total radium analyses made of Middle Trinity waters in Gillespie, Kendall, and Kerr Counties had a range of 0.6 to 10.9 pCi/l with an average concentration of about 5.7 pCi/l. The 10.9 pCi/l concentration was detected in the water from a well which is in Fredericksburg, and which is believed to be completed in the Middle Trinity and Hickory aquifers. Also, a 5.3 pCi/l total radium concentration was detected in the water from a Middle Trinity well at Ingram in Kerr County. Both of these analyses have total radium concentrations that exceed the total radium MCL of 5.0 pCi/l.

The results of these limited radioactive analyses indicates that waters of the Hickory aquifer within the study area are seriously contaminated with excessive levels of total radium. Excessively high total radium concentrations have been detected in Hickory waters in Mason and McCulloch Counties (Bluntzer, 1988). Also, other radioactive samples from wells in Llano, San Saba, and other parts of Mason and McCulloch Counties have detected excessively high radium concentrations in Hickory waters. Consequently, excessively high radium concentrations seem to be an inherent problem regionally with the use of Hickory waters for drinking purposes.

The one alpha analyses (59 pCi/l) for the water from the Mid-Cambrian well in Gillespie County strongly indicates that the Mid-Cambrian aquifer may have a serious problem with radioactive waters. Additional analyses for total radium as well as alpha radiation are needed of the waters from this well and other Mid-Cambrian aquifer wells to confirm this apparent problem.

The limited number of alpha analyses for Ellenburger-San Saba waters indicates that the aquifer has no apparent problem with radioactivity within the study area. Recent radioactive analyses of Ellenburger-San Saba waters from the San Saba member and the Gorman and Tanyard Formations (Table 1) in McCulloch and San Saba Counties north of the study area have provided similar results and the same conclusion. However, a recent analyses for alpha of the water from a well completed in the Honeycut Formation of the Ellenburger Group (Table 1) in southern Burnet County (just outside the study area) had an alpha concentration 10 pCi/l greater than the MCL of 15 pCi/l.

The one alpha analysis (4.4 pCi/l) for the water from the one Marble Falls well in Gillespie County indicates that the Marble Falls aquifer may not have a problem with radioactive waters. However, additional selected analyses for radioactivity of Marble Falls waters are needed to more accurately confirm this conclusion.

The total radium analyses for Middle and Lower Trinity waters apparently indicate that these aquifers locally may have problems with excessive radium concentrations. The one well at Fredericksburg with water excessively high in total radium (10.9 pCi/l) is understandable, since the well is completed in the hydrologically connected Middle Trinity and Hickory aquifers. The excessively high total radium concentrations detected in the Lower Trinity water at Comfort (6.0 pCi/l) and the Middle Trinity water at Ingram (5.3 pCi/l) are not fully understood. Additional water samples for radioactive analyses are needed from these wells as well as other Lower and Middle Trinity aquifer wells to confirm if high radioactivity is a local and/or regional problem with waters from the Trinity Group aquifers.

Radon which is a strongly radioactive gas is a radioactive decay product of certain specific isotopes of radium. The radon-222 isotope is the radioactive decay product of radium-226. Cech and others, 1988 detected high concentrations of radon-222 in ground waters from the Hickory aquifer in McCulloch County north of the study area. Water wells completed in aquifers having concentrations of radium are probably conveyors of radon gas to the land surface. Also, water pumped by such wells can deliver radon gas to dwellings and other enclosed structures where it can become concentrated and pose the greatest health risk. Radon at elevated levels poses greater health risks than any other constituent currently regulated by the Safe Drinking Water Act. However, a primary drinking water standard MCL for radon has not yet been determined. In the future when selected radioactive analyses are made in the study area, such analyses should attempt to include the analyses for radon-222. Additional information on alpha radiation (gross alpha), radium, and radon as well as other radioactive constituents in water are provided in Appendix A.

The most likely source for the excessive radium concentrations in Hickory waters may be from high concentrations of radioactive minerals which were derived from underlying Precambrian rocks and deposited in a specific bed or beds within the Hickory sandstone member of the Riley Formation (Table 1). These radioactive beds may be readily delineated in the boreholes of existing and future Hickory wells by the use of commercially available borehole geophysical logs. After the radioactive beds have been delineated, they can be sealed-off and prevented from supplying the radioactive water directly to the well bore. This method of controlling the production of radioactive ground water has been used in the Gulf Coast aquifer of southeast Texas with some success. However, the use of this method on a large-capacity well for public supply may seriously reduce well specific capacity to such an extent that the well may not be capable of performing as a reliable, long-term water supply.

GROUND-WATER AVAILABILITY

Utilization and Development of Ground Water

Historically, ground-water pumpage from the various aquifers has been used mainly for public supply, rural domestic, irrigation and livestock watering purposes. As an example, in 1985 these combined uses amounted to about 18,613 acre-feet or about 99.3 percent of the 18,739 acre-feet of total estimated ground-water pumpage. Of the 18,613 acre-feet amount; 8,086 acre-feet was used for public supplies, 5,896 acre-feet was used for rural domestic water supplies, 2,390 acre-feet was used for irrigation, and 2,241 acre-feet was used for livestock watering. The remaining 126 acre-feet which is less than one percent of the total pumpage was used for manufacturing and mining purposes. Of the 377 estimated large-capacity wells which were accounted for as having been used in 1985; 278 wells or 73.7 percent were used for public supply purposes, one well or about 0.3 percent was used for manufacturing purposes, and 98 wells or 26.0 percent were used for irrigation. The number of wells used for rural domestic water supplies, mining purposes and livestock watering are unknown.

In 1985, about 7,203 acre-feet of ground water was pumped from the Trinity Group aquifers using about 321 large-capacity wells for public supply, manufacturing and irrigation purposes. An unknown number of additional wells were used to pump about 6,760 acre-feet for rural domestic supplies (5,029 acre-feet), mining (105 acre-feet) and livestock watering (1,626 acre-feet). The largest centers of ground-water pumpage for public supply from the Trinity Group aquifers in 1985 included Kerrville (872 acre-feet using 13 wells), Ingram (376 acre-feet using 4 wells), Wimberly (363 acre-feet using 5 wells), Boerne (336 acre-feet using 8 wells), Dripping Springs (294 acre-feet using 2 wells), Comfort (217 acre-feet using 5 wells) and Bandera (199 acre-feet using 3 wells). In 1985, Kerrville also used about 2,870 acre-feet of surface water from Quinlan Creek and the Guadalupe River, and Boerne also used about 451 acre-feet from a city lake on Cibolo Creek. Other centers of ground-water pumpage include the Canyon Lake area of Comal County where about 23 private water companies pumped about 1,068 acre-feet using about 60 wells, and the Wimberly area in Hays County where a private water company pumped about 493 acre-feet using 3 wells. In 1985, approximately 2,379 acre-feet of ground water from the Trinity Group aquifer was pumped for irrigation by approximately 68 wells in Bandera County (12 wells), Blanco County (6 wells), Gillespie County (24 wells), Kendall County (12 wells), and Kerr County (14 wells).

The second most used aquifer is the Ellenburger-San Saba aquifer in Gillespie and Blanco Counties. In 1985, about 2,545 acre-feet of ground water was pumped using about 28 large-capacity wells for public supply and irrigation purposes. An unknown number of additional wells were used to pump about 266 acre-feet for rural domestic supplies (141 acre-feet), mining (16 acre-feet) and livestock watering (109 acre-feet). The largest centers of ground-water pumpage for public supply in 1985 included Fredericksburg (1,828 acre-feet using 5 wells) and Johnson City (152 acre-feet using 2 wells). In 1985, Johnson City supplemented their supply from the Ellenburger-San Saba aquifer with about 58 acre-feet of surface water from the Pedernales River. Approximately 526 acre-feet of ground water was pumped in 1985 from the Ellenburger-San Saba aquifer for irrigation in Blanco County (6 wells) and Gillespie County (10 wells).

The third most used aquifer is the Edwards Plateau aquifer in Bandera, Gillespie, and Kerr Counties. In 1985, only about 110 acre-feet of ground water was pumped using 4 large-capacity wells for public supply and irrigation purposes. An unknown number of additional wells were used to pump about 982 acre-feet for rural domestic supplies (586 acre-feet) and livestock watering (396 acre-feet). The only center of pumpage for public supply was one private water company well near Harper in Gillespie County which withdrew about 7 acre-feet of ground water in 1985. Approximately 103 acre-feet was pumped in 1985 from the Edwards Plateau aquifer by 3 irrigation wells in Gillespie County.

The Hickory is the fourth most used aquifer in the study area. In 1985, about 614 acre-feet of ground water was pumped using 21 large-capacity wells for public supply and irrigation purposes in Blanco and Gillespie Counties. An unknown number of additional Hickory wells were used to pump about 157 acre-feet for rural domestic supplies (93 acre-feet) and livestock watering (64 acre-feet). Approximately 203 acre-feet of Hickory water was pumped by Fredericksburg in 1985 using one well within the city and two wells north of the city in north-central Gillespie County. Part of the water from the well in the city is produced from the Middle Trinity aquifer (Hensell sand). Since waters from these wells have excessive concentrations of radium, the wells are used only to supplement the city's supply from the Ellenburger-San Saba aquifer during peak summertime demands. In 1985, about seven additional privately owned wells were used in the Fredericksburg area to pump about 29 acre-feet of Hickory water for public supply purposes. Approximately 382 acre-feet of Hickory water was pumped for irrigation purposes in Blanco County (2 wells) and Gillespie County (9 wells).

Relatively small amounts of additional ground water are pumped from the Mid-Cambrian, Marble Falls and Precambrian aquifers in Blanco, Gillespie and Travis Counties. In 1985, approximately 51 acre-feet was pumped from the Mid-Cambrian aquifer for rural domestic supplies (25 acre-feet) and livestock watering (26 acre-feet). Approximately 29 acre-feet was pumped from the Marble Falls aquifer for public supply (6 acre-feet for a rural subdivision in Travis County), rural domestic supplies (12 acre-feet) and livestock watering (11 acre-feet). Approximately 22 acre-feet was pumped in 1985 from Precambrian aquifers for public supply (3 acre-feet in northern Gillespie County for Enchanted Rock State Park), rural domestic supplies (10 acre-feet) and livestock watering (9 acre-feet).

The approximate ground-water pumpage (acre-feet) and the approximate number of large-capacity wells used in 1985 by use category, by aquifer are presented in Table 13. The estimated 1985 ground-water pumpage by county, by use category, by aquifer, and corresponding estimated number of large-capacity wells used in 1985 are provided in Appendix D. Figure 23 provides the locations of most of the large-capacity wells used in the study area, and graphs showing the annual amounts of ground-water and surface-water used from 1955 through 1986 by 14 selected municipalities, water districts and water supply corporations.

Table 13.-Approximate Ground-Water Pumpage in Acre-Feet and Number of Large-Capacity Wells Used in 1985 (A-F means acre-feet. U means number of wells used is unknown)

Use Category	Edwards Plateau Aquifer		Trinity Group Aquifers		Marble Falls Aquifer		Ellenburger-San Saba Aquifer		Mid-Cambrian Aquifer		Hickory Aquifer		Precambrian Aquifer		Total		Percent of Totals	
	Pumpage (A-F)	No. Wells	Pumpage (A-F)	No. Wells	Pumpage (A-F)	No. Wells	Pumpage (A-F)	No. Wells	Pumpage (A-F)	No. Wells	Pumpage (A-F)	No. Wells	Pumpage (A-F)	No. Wells	Pumpage (A-F)	No. Wells	Pumpage (A-F)	Used Wells
Major Public Supply	—	—	4,431	105	—	—	1,980	7	—	—	203	3	—	—	6,614	115	35.3	30.5
Other Public Supply	7	1	1,388	147	6	2	39	5	—	—	29	7	3	1	1,472	163	7.8	43.2
Rural Domestic Supply	586	U	5,029	U	12	U	141	U	25	U	93	U	10	U	5,896	U	31.5	—
Manufacturing	—	—	5	1	—	—	—	—	—	—	—	—	—	—	5	1	<0.1	0.3
Power	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Mining	—	—	105	U	—	—	16	U	—	—	—	—	—	—	121	U	0.6	—
Irrigation	103	3	1,379	68	—	—	526	16	—	—	382	11	—	—	2,390	98	12.8	26.0
Livestock	396	U	1,626	U	11	U	109	U	26	U	64	U	9	U	2,241	U	12.0	—
Total Pumpage and Large-Capacity Wells Used	**1,092**	**4**	**13,963**	**321**	**29**	**2**	**2,811**	**28**	**51**	**U**	**771**	**21**	**22**	**1**	**18,739**	**377**	**100.0**	**100.0**
Percent of Totals	5.8	1.1	74.5	85.1	0.2	0.5	15.0	7.4	0.3	—	4.1	5.6	0.1	0.3	100.0	100.0	—	—

Estimated Ground Water Available for Future Development

Based on evaluations of estimated historical base flow, estimated underflow of ground waters, and distribution of historical annual rainfall, the aquifers within the study area receive about 450,000 acre-feet of average annual natural recharge which equates to about 5 percent of the average annual rainfall of about 9.0 million acre-feet. Coupled with the relatively large but unknown amount of ground water in transit storage, it would seem apparent that this very large amount of ground water which is physically available on a perennial basis would be more than adequate to fulfill the expected water-supply needs for many decades without any problems. However, only a very small portion of this relatively large amount of ground water can be realistically recovered by wells on a sustained basis. This condition is due to the extremely low coefficients of transmissibility and storage of the aquifers; particularly those of the Trinity Group aquifers. This condition coupled with the inability or unwillingness of many of the ground-water users in the area to practice and use more prudent ground-water exploration and drilling techniques, proper well spacing, and proper well construction and/ or well development, causes extreme water-level declines within and near centers of ground-water withdrawals for public supply purposes.

Throughout the study area, very significant, long-term net water-level declines have occurred historically within and near centers of pumpage for public supply purposes. Evaluations of historical water-level declines, historical ground-water pumpage trends, and historical available drawdowns (amounts of artesian heads above the top of the aquifer) indicate that future available drawdowns would be depleted by the year 2000 at Fredericksburg's Hickory Well No. 18, Bandera's Lower Trinity Well No. 4 and Kerrville's Lower Trinity Well No. 4 (using the historical water-level decline trend and the historical pumpage trend before surface water was used at Kerrville). Similar depletion of available drawdown was determined for the St. Stephens School Lower Trinity Well in Travis County where a very small amount of pumpage has depleted available drawdown at a net rate of about 4 feet per year.

Examinations of long-term, historical, net water-level declines at and near Bandera, Dripping Springs, Comfort, and Boerne indicate much less rates of historical, net water-level declines, but a more widespread gradual depletion of water from storage in the Middle Trinity aquifer; particularly in eastern Kerr, western Kendall, and eastern Bandera Counties. If continued, this gradual depletion or mining of Middle Trinity aquifer storage will cause a decrease of aquifer transmissibility which in turn will cause well yields to severely decrease. As well yields decrease, more and more wells will be required to meet expected water needs. If such additional wells are not properly located and constructed, water levels and well yields will continue to decline at even more alarming rates. In addition, as storage is depleted in the Middle Trinity aquifer, waters with excessive sulfate contents in the evaporite beds of the overlying Upper Trinity aquifer may be induced to leak downward into the Middle Trinity aquifer and deteriorate ground-water quality.

Considering water-level declines in and near areas of concentrated public supply pumpage and the potential downward leakage of poor quality water, a method was developed to estimate the sustained yield of the Trinity Group aquifers. Using hydrographs of historical water levels from observation wells in and near centers of pumpage and the historical records of annual pumpage, an annual sustained yield "duty" was determined for an approximate specific area which was estimated to be influenced by pumpage from the Trinity Group aquifers. The duty (expressed in acre-feet per year per square mile - af/yr/mi^2) was determined using an estimated average annual pumpage within an estimated specific area influenced by such pumpage during a selected period of years when hydrographs indicated an apparent stabilization of water levels. This method is not highly accurate 1) because the area of pumpage influence (mi^2) had to be selected based on limited available data on distribution of pumpage and aquifer characteristics, and 2) because of the very limited number of observation wells and limited water-level data available to provide meaningful hydrographs for determination of periods of apparent water-level stabilization within and near the area influenced by the pumpage. However, the available data (water-levels and pumpage) was considered to be sufficient to provide a reasonably accurate perspective on the annual sustained yield of the Trinity Group aquifers to prevent adverse long-term water-level declines and related adverse encroachment of poor quality water.

Sufficient data was available to estimate sustained yield "duties" for the Trinity Group aquifers at and near Kerrville, Bandera, Boerne, Comfort, and the St. Stephens School area of Travis County. Using these results and other hydrogeological knowledge of the Trinity Group aquifers, estimated duties were distributed on an areal basis by county. The annual sustained ground-water yield (af/yr) of the Trinity Group was then calculated by multiplying the distributed estimated duties (af/yr/mi^2) and the relevant areas (mi^2) where the aquifers were determined to occur within each county.

The annual sustained yield "duties" determined for the Trinity Group aquifers were used to estimate annual sustained yield "duties" for the Edwards Plateau aquifer. Sufficient water-level and pumpage data were not available to use the "duty" method to estimate the annual sustained yields of the various Paleozoic aquifers. Instead, the average annual amounts of natural recharge previously determined for the various Paleozoic aquifers are accepted as reasonably accurate estimates of average annual sustained yields.

The approximate annual sustained yields (acre-feet per year-af/yr) for the Cretaceous and Paleozoic aquifers are provided in Table 14. The estimated total annual ground-water sustained yield of 46,000 acre-feet for the study area only amounts to about 10 percent of the area's estimated average annual natural recharge of 450,000 acre-feet. The 46,000 acre-feet annual sustained yields of the Cretaceous and Paleozoic aquifers is the approximate amount of ground water that can be recovered by wells without adversely effecting baseflow (ground-water discharge) to area effluent streams, and without causing adverse water-level declines and related encroachment of poor quality water; particularly in the Trinity Group aquifers.

Table 14.- Approximate Annual Sustained Yields in Acre-Feet Per Year for the Paleozoic and Cretaceous Aquifers

County	Edwards Plateau Aquifer (af/yr)	Trinity Group Aquifers (af/yr)	Marble Falls Aquifer (af/yr)	Ellenburger -San Saba Aquifer (af/yr)	Mid-Cambrian Aquifer (af/yr)	Hickory Aquifer (af/yr)	Total Annual Sustained Yield (af/yr)
Bandera	700	6,500	—	—	—	—	7,200
Blanco	100	1,600	300	4,600	300	800	7,700
Comal	—	1,800	—	—	—	—	1,800
Gillespie	1,400	3,400	—	4,000	300	2,000	11,100
Hays	—	1,800	—	—	—	—	1,800
Kendall	400	4,400	—	—	—	—	4,800
Kerr	2,600	7,200	—	—	—	—	9,800
Medina	—	900	—	—	—	—	900
Travis	—	900	—	—	—	—	900
Totals For Study Area	**5,200**	**28,500**	**300**	**8,600**	**600**	**2,800**	**46,000**

The results obtained from the use of the "duty" method to estimate the sustained yield of the Trinity Group aquifers admittedly could be somewhat inaccurate because of the limited amount of water-level and pumpage data and information available for application of the method. At best, the resulting sustained yield of 28,500 acre-feet per year for the Trinity Group aquifers should be considered to be a gross approximation. Even if the annual sustained yield of the Trinity Group aquifers is 50 to 100 percent greater (which is very doubtful) additional water supplies need to be developed to meet long-term projected water demands expected in and adjacent to current centers of pumpage for public water supply purposes.

Additional ground water for public supply purposes is available in the Trinity Group aquifers in remote areas which are considerable distances from the current centers of pumpage. In 1985, approximately 13,963 acre-feet of ground water was withdrawn by wells from the Trinity Group aquifers. This amount probably represents the average annual withdrawal by wells from the aquifers during the middle and late 1980s. If the average annual withdrawal from the aquifers was approximately 14,000 acre-feet, then approximately 14,500 acre-feet per year of additional ground water would be available in the remote areas away from current centers of pumpage. However, development of this remote additional available ground water for public supply purposes would entail great costs for additional lands, properly located, constructed and operated wells, additional water delivery facilities, and in some cases additional water storage facilities. Significantly large amounts of additional water for public supply purposes is physically available from the base flow and storm runoff of the area's streams; particularly the Pedernales, Guadalupe, Blanco and Medina Rivers. However, acquisition and development of such waters also will entail great costs, and in most cases contractual arrangements between water users and water suppliers (holders of surface-water rights).

It is very apparent that conjunctive use of ground water and surface water on a regional scale is the proper means of meeting future public water supply needs. Such a regional program needs to be implemented in a timely manner through careful planning, appropriate coordination and arrangements between water users and water suppliers and the willingness of water users to pay the high costs for future adequate and safe public water supplies. Within the last 10 years conjunctive use of ground water and surface water has been practiced successfully by the public water supply systems at Kerrville, Boerne, and Johnson City. Similar conjunctive use programs need to be implemented at Bandera, Fredericksburg, Blanco, Comfort, Ingram, and urban areas adjacent to all of the above major communities, and in other portions of eastern Bandera County, northwestern Comal County, northwestern Hays County, and southwestern Travis County.

Artificial Recharge of Ground Water

The best method or methods for artificial recharge of an aquifer should use proper amounts of water with appropriate quality, and recharge facilities that are capable of delivering waters into the saturated thickness in a timely and efficient manner. Artificial recharge operations should be strategically located in an area or areas where the recharged waters can be effectively stored and subsequently recovered for beneficial uses (modified from Bluntzer, 1988). Artificial recharge by direct methods include injection by wells into and/or just above the zone of saturation or by spreading of water at the land surface above the zone of saturation with the use of special surface facilities and means such as pits, trenches, basins, stream channel modifications, flooding, irrigation and ditch and furrow (O'Hare and others, 1986). The spreading method at the land surface assumes that waters being applied will infiltrate through the unsaturated zone above the aquifer and move downward and replenish the zone of saturation. Therefore, the spreading method can only be effectively used in areas where the aquifer is under water-table (unconfined) conditions. Artificial recharge by wells can be used in areas where aquifers are under water-table (unconfined) conditions or under artesian (confined) conditions.

If artificial recharge of the Cretaceous and Paleozoic aquifers is considered, a detailed data collection program and a detailed hydrogeological study of the aquifer and the area to be recharged should be completed to determine: 1) the geological conditions (stratigraphy and structure) related to the occurrence of all water-bearing and non-water-bearing units; 2) the amount, distribution and extent of saturated thickness and the hydraulic properties of the aquifer; 3) the amount, distribution and extent of any measurable dewatered portion of the aquifer, if all or part of such aquifer is under water-table (unconfined) conditions; 4) the natural ground-water recharge, movement and discharge of the aquifer, and the ground-water and surface-water relationships in and adjacent to the area; 5) the amounts of ground water historically and currently withdrawn from all large-capacity wells and the location and aquifer designation of each well; 6) the water quality characteristics of all ground waters, and the identification of existing and potential water-quality problems; 7) the approximate amount, water quality characteristics and existing and potential water-quality problems of available source water or waters intended for artificial recharge of the aquifer; 8) if the quality of the source water or waters is compatible with the water quality of the aquifer, and is suitable for recharge operations, aquifer storage and later recovery for beneficial uses; 9) the most suitable method for artificial recharge of the aquifer; and 10) if water rechargers and/or users will physically and economically benefit from artificial recharge operations.

In Texas, ground-water use is an inherent property right and landowner's may withdraw as much ground water as physically possible as long as the water is used for beneficial purposes and is not wasted. When water is artificially recharged into an aquifer, such water physically becomes ground water, and consequently becomes the property of all landowners who physically have access to such water and are capable and willing to recover such water for beneficial uses. Therefore, the lateral extent of the aquifer that artificial recharge will enhance needs to be determined, so that the landowner conducting the recharge-recovery operations will be the sole or at least the primary beneficiary on some economical basis. Otherwise, special arrangements between all landowners who would physically and economically benefit from such recharge-recovery operations would need to be made on a reasonably equitable basis.

An artificial recharge study for the Hickory Underground Water Conservation District No. 1 in the Katemcy Creek basin of northern Mason and southern McCulloch Counties (Bluntzer, 1988) recommended that surface-water runoff be retained in small reservoirs and artificially recharged to the Hickory aquifer by wells; either through dual purpose recharge-recovery wells or through wells specifically constructed for recharge. The use of wells as the recharge method would assure that artificial recharge operations could be more readily controlled, and would allow the recharged water to be more efficiently placed into aquifer storage for beneficial recovery and use without significant loss or escape. The use of spreading methods for artificial recharge of the Hickory aquifer were determined to be undesirable, because there were no reasonable assurances that most of the recharged waters would not be lost or not escape from the area where the waters could be later recovered from aquifer storage for beneficial use. However, the study recommended that artificial recharge by wells be tested before funds were expended for the construction of an expensive surface-water retention structure. Even though the study concluded that artificial recharge could be accomplished physically, the District wisely decided that artificial recharge would not be economically feasible, because one very costly retention structure only would provide enough artificially recharged water for a very limited number of water users (irrigators) within a relatively small portion of the total area that needed to be benefited by artificial recharge.

A test to demonstrate the physical feasibility of artificial recharge was made in March 1955 by the U. S. Geological Survey at Kerrville by using City Well No. 5 as the injection (recharge) well and City Well Nos. 4 and 7 as water-level monitoring wells. According to Reeves (1969), the following information and conclusions resulted from this artificial recharge test of the Lower Trinity aquifer. 1) Water-level measurements in the injection well (City Well No. 5) indicated a rise in water level of about 25 feet due to the injection of 400 gpm for 24 hours. 2) The theoretical rise in water level at the injection well using an injection rate of 1,000 gpm would be about 62.5 feet for one day or 87.5 feet for 100 days. The actual rise may be somewhat more because of turbulence and frictional losses in and around the well. 3) It was concluded that water could be injected at a rate of at least 1,000 gpm. 4) The recharge water would probably require treatment to prevent clogging of recharge wells and the aquifer. 5) The Guadalupe River is the obvious source of water for artificial recharge purposes. 6) Additional studies should be made to determine the economic feasibility of using treated Guadalupe River water for artificial recharge of the Lower Trinity aquifer at Kerrville.

Guyton (1973) addressed artificial recharge at Kerrville and indicated the following very important points and conclusions. 1) Since it is usually much more difficult to inject (recharge) water into a well than it is to produce the water from the well by pumping, each specific artificial recharge project is a new experiment in itself. 2) Theoretical mathematical computations are available that readily show that artificial recharge is simply the reverse of pumping. However, such things as bacteria, suspended matter, corrosion products, and entrained air introduced with recharge waters can readily clog recharge wells. Such things do not adversely affect producing wells. 3) The chemical quality of the recharge water and the chemical quality of the water in the aquifer should be compatible, so that the recharge well and the aquifer are not clogged with undesirable chemical deposits. Also clogging of the aquifer is possible due to the swelling of clays in the aquifer caused by the chemical character of the recharge water. 4) Even though the U.S. Geological Survey's artificial recharge test of relatively short duration at Kerrville in 1955 was reported to be successful, a much longer test of several months using surplus water from the Guadalupe River would be more appropriate to determine the practicality of artificial recharge. Such a longer test would determine if the potential problems described in items 2 and 3 above would cause artificial recharge to be unfeasible. 5) Because of the confined conditions of the Lower Trinity aquifer and the variable seasonal demands for a reliable water supply, it would not be advantageous to practice artificial recharge at Kerrville, unless sufficient amounts of acceptable quality recharge water are available during reasonable and timely parts of every year.

The Upper Guadalupe River Authority which provides a large part of the City of Kerrville's water supply currently is conducting an artificial recharge study in the Kerrville area. The study will be conducted in three phases to determine the physical and economical feasibility for artificial recharge of the Lower Trinity aquifer with surplus treated water from the Guadalupe River during "wet" months and then recovering the recharged waters during "dry" months to meet Kerrville's peak water demands. This concept is intended to allow the Authority to use dual purpose wells to meet increasing peak water demands without immediate expansion of the Authority's water-treatment facilities. If successful, this aquifer storage and recovery (ASR) project would allow more economical use of the Authority's current and future water-treatment facilities and at the same time physically enhance the public water supply for Kerrville (CH2M Hill, 1988).

To date, phase one and a portion of phase two of the project have been completed. This part of the project determined the hydrogeology of the Lower Trinity aquifer at the proposed ASR site. The remaining part of the second phase of the project began in 1990 and consists of a long-term testing program on a prototype ASR well. If ASR is determined to be physically and economically feasible at the proposed ASR site, phase three of the project will establish, operate, and maintain an ASR well field. Five such ASR facilities have been successfully established and operated in Florida since 1983, New Jersey since 1968, and California since 1978 (CH2M Hill, 1988 and 1989).

If the ASR project at Kerrville proves to be successful, similar projects should be considered for the enhancement of public water supplies at Bandera, Comfort, Boerne and perhaps other public water supply systems in the study area and other parts of the State. However, such artificial recharge projects will not be physically and economically feasible unless a sufficient supply of suitable quality surface water is available on a timely basis for treatment, recharge and recovery for beneficial use, and unless the entity conducting the recharge-recovery operations will be the sole or at least the primary beneficiary.

HISTORICAL AND PROJECTED POPULATION, HISTORICAL WATER USE AND PROJECTED WATER DEMANDS

Historical and Projected Population

In 1985, the population of the study area was concentrated mostly in and adjacent to the incorporated cities and towns; namely Kerrville, Fredericksburg, Boerne, West Lake Hills, Ingram, Lakeway, Dripping Springs, Blanco, Bandera, Johnson City, Woodcreek, Bee Cave and Briarcliff. In addition, significant, unincorporated population centers included the communities of Wimberley, Comfort, Hunt, Center Point, Harper, and Stonewall. In 1985, approximately 38 percent of the population of 125,924 resided in these incorporated and unincorporated communities. Also, significant concentrations of urban type population reside in rural residential subdivisions adjacent to these incorporated and unincorporated communities and in and adjacent to the Interstate Highway 10 corridor in Kerr and Kendall Counties and northwest of the Interstate Highway 35 corridor in Comal County (near Canyon Lake), Hays County (near Wimberley and Dripping Springs) and Travis County (near Lake Travis and the U.S. Highway 290 West and State Highway 71 West corridors).

From 1980 to 1985 the historical population increased from 98,204 to 125,924 which is a 28 percent increase in population for the five year period or an increase of about 5.6 percent per year (%/yr.). During the same period, population increases occurred within the study area with a 48 percent (9.6%/yr.) increase in Travis County; a 42 percent (8.4%/yr.) increase in Comal County, a 40 percent (8.0%/yr.) increase in Hays County, a 32 percent (6.4%/yr.) increase in Kendall County, a 26 percent (5.2 %/yr.) increase in Bandera County, a 17 percent (3.4 %/yr.) increase in Kerr County, a 14 percent (2.8%/yr.) increase in Gillespie County, and a 14 percent (2.8%/yr.) increase in Blanco County. The only area which had a decease in population from 1980 to 1985 was northern Medina County where there was a slight decrease of less than one (1) percent.

Similar population growth is expected to continue through the year 2010; especially in those portions of Hays, Comal and Travis Counties within the study area and Blanco, Bandera, Kendall and Kerr Counties, all of which are within the study area. From 1985 through 2010, the population is expected to increase from 125,924 to 219,874 which is a 75 percent increase for the 25 year period or an increase of 3.0 percent per year. For the 25 year period, population increases are expected to occur with the following projected increases: 134 percent (5.4%/yr) in Hays County, 108 percent (4.3%/yr.) in Comal County, 97 percent (3.9%/yr.) in Blanco County, 87 percent (2.5%/yr.) in Travis County, 63 percent (2.5%/yr.) in Bandera County, 62 percent (2.5%/yr.) in Kendall and Kerr Counties, 47 percent (1.9%/yr.) in Gillespie County and 24 percent (1.0%/yr.) in Medina County. Such population growth is expected to be concentrated in and adjacent to such communities as Kerrville, Fredericksburg, Boerne, West Lake Hills, Ingram, Lakeway, Dripping Springs, Blanco, Bandera, Johnson City, Woodcreek, Bee Cave, Briarcliff, Wimberley, Comfort, Hunt, Center Point, Harper and Stonewall. Table 15 presents the 1980 and 1985 historical population and the 1990, 2000, and 2010 projected population by county and selected major cities.

The 1980 and 1985 population figures were determined from U. S. Bureau of Census statistics and information. Population projections (1990-2010) were estimated by extending U. S. Bureau of Census statistics according to growth rates used in the 1988 Texas Water Development Board Revised Data Series population projection methodology. The "County Other" population as indicated in Table 15 includes specified incorporated and unincorporated communities and all rural population. The population figures given are for the entire counties of Bandera, Blanco, Gillespie, Kendall and Kerr, and only those parts of Comal, Hays, Medina and Travis Counties within the study area (Figure 1).

Historical Water Use

The total amount of water used in 1985 was about 30,430 acre-feet with 18,739 acre-feet or 61.6 percent from ground-water sources and 11,961 acre-feet or 38.4 percent from surface-water sources. In 1980, the total amount of water used was about 25,035 acre-feet with 17,828 acre-feet or 71.2 percent from ground-water sources and 7,207 acre-feet or 28.8 percent from surface-water sources. The 1985 total water use of 30,430 acre-feet was 21.5 percent greater than the 1980 water use, and was the result of increases in water used for public supply and rural domestic supply purposes. From 1980 to 1985, water used for public and rural domestic water supplies increased from 15,964 acre-feet to 22,872 acre-feet which was a 43.3 percent increase. Table 16 provides the estimated amounts of water used in 1980 and 1985 by water use categories and by sources (ground water and surface water). The estimated water used in 1980 and 1985 by county is provided in Appendix E.

The approximate 1980 and 1985 water use which is provided in Table 16 and Appendix E was compiled as documented in Texas Water Development Board, 1988. Much of the public supply water use was obtained from the amounts reported to the Board by public water systems (cities, towns, water supply corporations, water districts, private water companies, etc.). Public water use not reported to the Board and rural domestic water use was computed using appropriate population and average per capita water use. Livestock water use was computed based on the rural geographical area (square miles) apportioned to county total livestock use. All other water uses were compiled based on site-specific computed use.

Figure 23 provides graphs showing the historical annual water use through 1986 for 14 public water supply systems. As indicated, 10 of these systems historically have used ground water only, and include Bandera, Bandera Fresh Water Supply District No. 1, Medina Water Supply Corporation, Ingram, Kendall County Water Control and Improvement District No. 1 (Comfort), Fredericksburg, Dripping Springs Water Supply Corporation, Wimberley Water Supply Corporation, Haskin Water Supply, Inc., and Bulverde Hills Water System. The public water systems at Kerrville, Johnson City and Boerne historically have used ground water and surface water. Blanco which has not developed a reliable ground-water supply uses only surface water from the Blanco River.

Table 15.-Historical Population in 1980 and 1985 and Projected Population in the Years 1990, 2000 and 2010

County/City/Other	1980	1985	1990	2000	2010
Bandera County					
Bandera	947	1,071	2,389	3,441	3,979
County Other	6,137	7,835	7,533	9,108	10,532
County Totals	7,084	8,906	9,922	12,549	14,511
Note:	*"County Other" includes population in the unincorporated communities of Bandera Falls, Lakehills, Medina, Pipe Creek, Tarpley and Vanderpool, rural residential subdivisions and the remaining rural area of the county.*				
Blanco County					
Blanco	1,179	1,346	1,847	2,472	3,109
Johnson City	872	909	1,340	1,780	2,238
County Other	2,630	3,068	3,238	4,087	5,137
County Totals	4,681	5,323	6,425	8,339	10,484
Note:	*"County Other" includes population in the unincorporated communities of Cypress Mill, Flugrath, Hye, Rocky Creek, Round Mountain, Sandy and Twin Sisters, rural residential subdivisions and the remaining rural area of the county.*				
Comal County					
County Other	4,648	6,589	7,901	11,140	13,702
Note:	*"County Other" includes population in the incorporatedportion of Fair Oaks Ranch in the county, the unincorporated portion of Silver Hills in the county, the unincorporated communities of Bulverde, Canyon City, Fischer, Oak Cliff Acres, Smithson Valley, Spring Branch and Startzville, numerous rural residential subdivisions and the remaining rural area of the county.*				
Gillespie County					
Fredericksburg	6,412	7,375	8,449	10,118	11,275
County Other	7,120	8,111	8,694	10,274	11,450
County Totals	13,532	15,486	17,143	20,392	22,725
Note:	*"County Other" includes population in the unincorporated communities of Albert, Cherry Springs, Doss, Eckert, Harper, Luckenbach, Stonewall and Willow City, numerous rural residential subdivisions and the remaining rural area of the county.*				
Hays County					
Dripping Springs	894	1,689	2,174	3,203	4,382
Wimberley	2,140	2,879	3,579	4,828	6,605
County Other	1,639	1,966	1,349	2,979	4,316
County Totals	4,673	6,534	7,102	11,010	15,303
Note:	*The historical and projected populations given for Drippings Springs and Wimberley includes all persons estimated to be within the service area of the respective water supply corporation. "County Other" includes population in the incorporated community of Woodcreek, the unincorporated communities of Driftwood and Henly, numerous rural residential subdivisions and the remaining rural area of the county.*				

Table 15.-Historical Population in 1980 and 1985 and Projected Population in the Years 1990, 2000 and 2010 *(cont'd.)*

County/City/Other	1980	1985	1990	2000	2010
Kendall County					
Boerne	3,229	4,685	4,434	5,139	5,910
Comfort	1,226	1,533	1,636	1,965	2,167
County Other	6,180	7,812	10,015	12,701	14,699
County Totals	10,635	14,030	16,085	19,805	22,776

Note: *The historical and projected population given for the unincorporated community of Comfort includes all persons estimated to be within the service area of the Kendall County Water Control and Improvement District No. 1. "County Other" includes population in the incorporated portion of Fair Oaks Ranch in the county, the unincorporated communities of Bergheim, Kendalia, Lindendale, Sisterdale, Waring and Welfare, numerous rural residential subdivisions and the remaining rural area of the County.*

Kerr County					
Kerrville	15,276	18,024	21,619	26,966	31,147
Ingram	1,820	2,465	2,630	3,159	3,560
County Other	11,684	13,097	13,571	17,030	19,760
County Totals	28,780	33,586	37,820	47,155	54,467

Note: *The historical and projected population given for the incorporated community of Ingram includes all persons estimated to be within the service area of the Ingram Water Supply system. "County Other" includes population in the unincorporated communities of Camp Verde, Center Point, Hunt and Mountain Home, numerous rural residential subdivisions and the remaining rural area of the county.*

Medina County					
County Other	627	625	624	685	773

Note: *"County Other" includes population in the unincorporated community of Mico, rural residential subdivisions and the remaining rural area of the county.*

Travis County					
Lakeway	2,758	5,566	7,414	9,875	10,892
West Lake Hills	2,166	3,492	4,650	6,564	8,079
County Other	18,620	25,787	25,884	36,476	46,162
County Totals	23,544	34,845	37,948	52,915	65,133

Note: *The historical and projected population given for Lakeway includes all persons estimated to be within the service area of the Lakeway Municipal Utility District. "County Other" includes population in the incorporated communities of Bee Cave and Briarcliff, numerous rural residential subdivision and the remaining rural area of the county.*

Total Population of Study Area	**98,204**	**125,924**	**140,970**	**183,990**	**219,874**

Table 16.-Approximate Water Used in 1980 and 1985

Water Use Category	Approximate 1980 Water Use in Acre-Fee Ground Water	Surface Water	Total Use	Approximate 1985 Water use in Acre-Feet Ground Water	Surface Water	Total Use
Major Public Supply	5,794	2,346	8,140	4,375	5,555	9,930
Other Public Supply	1,874	943	2,817	3,246	3,440	6,686
Subtotal Public Supply	7,668	3,289	10,957	7,621	8,995	16,616
Rural Domestic Supply	5,007	-0-	5,077	6,203	53	6,256
Subtotal Drinking Water Use	**12,675**	**3,289**	**15,964**	**13,824**	**9,048**	**22,872**
Manufacturing	536	84	620	163	123	286
Power	-0-	-0-	-0-	-0-	-0-	-0-
Mining	-0-	-0-	-0-	121	-0-	121
Subtotal Industrial Water Use	**536**	**84**	**620**	**284**	**123**	**407**
Irrigation	1,778	2,613	4,391	2,390	1,421	3,811
Livestock	2,839	1,221	4,060	2,241	1,099	3,340
Subtotal Agricultural Water Use	**4,617**	**3,834**	**8,451**	**4,631**	**2,520**	**7,151**
Total Water Use	**17,828**	**7,207**	**25,035**	**18,739**	**11,691**	**30,430**

Table 17. Approximate Water Used in 1980 and 1985 by Selected Major Public Water Systems

	Approximate Water Use in Acre-Feet		
County, Water System & Supply	**1980**	**1985**	**Source of Supply**
Bandera, City of Bandera			
From Ground-Water Supply	190	170	Trinity Group Aquifer
From Surface-Water Supply	-0-	-0-	None
Total Water Used	190	170	
Blanco, City of Blanco			
From Ground-Water Supply	-0-	-0-	None
From Surface-Water Supply	239	226	Blanco River
Total Water Used	239	226	
Note: *The City of Blanco currently has a surface-water permit for diversion of 600 acre-feet per year from the Blanco River.*			
Blanco, City of Johnson City			
From Ground-Water Supply	41	131	(See Note Below)
From Surface-Water Supply	147	51	Pedernales River
Total Water Used	188	182	
Note: *The City of Johnson City has a well field which produces ground water from the Ellenburger-San Saba aquifer. Also, the city currently has a surface-water permit for diversion of 200 acre-feet per year from the Pedernales River.*			
Gillespie, City of Fredericksburg			
From Ground-Water Supply	1,325	1,606	(See Note Below)
From Surface-Water Supply	-0-	-0-	None
Total Water Used	1,325	1,606	
Note: *The City of Fredericksburg has well fields which produce ground water from the Ellenburger-San Saba aquifer, Hickory aquifer and Middle Trinity aquifer (Hensell sand).*			
Hays, Dripping Springs WSC			
From Ground-Water Supply	125	294	Trinity Group Aquifer
From Surface-Water Supply	-0-	-0-	None
Total Water Used	125	294	
Note: *The water use for the Dripping Springs Water Supply Corporation (WSC) includes water used by residence within the incorporated community of Dripping Springs and by residence adjacent to the community within the service area of the WSC.*			
Hays, Wimberley WSC			
From Ground-Water Supply	263	363	Trinity Group Aquifer
From Surface-Water Supply	-0-	-0-	None
Total Water Used	263	363	
Note: *The water use for the Wimberley Water Supply Corporation (WSC) includes water used by residence area of the WSC.*			
Kendall, City of Boerne			
From Ground-Water Supply	233	326	Trinity Group Aquifer
From Surface-Water Supply	381	451	Cibolo Creek
Total Water Used	614	777	
Note: *The City of Boerne currently has a permit for diversion of 833 acre-feet per year from a city lake on Cibolo Creek.*			

continued

Table 17.Approximate Water Used in 1980 and 1985 by Selected Major Public Water Systems *(cont'd.)*

	Approximate Water Use in Acre-Feet		
County, Water System & Supply	**1980**	**1985**	**Source of Supply**
Kendall, Kendall Co. WCID No.1			
From Ground-Water Supply	146	217	Trinity Group Aquifer
From Surface-Water Supply	-0-	-0-	None
Total Water Used	146	217	
Note:The water use for the Kendall County Water Control and Improvement District (WCID) No. 1 includes water used by residence within and adjacent to the unincorporated community of Comfort.			
Kerr, City of Kerrville			
From Ground-Water Supply	3,178	850	Trinity Group Aquifer
From Surface-Water Supply	96	2,844	Guadalupe River
Total Water Used	3,274	3,694	
Note:The City of Kerrville currently has a permit for diversion of 155acre-feet per year from the Guadalupe River and Quinlan Creek. Kerrville's major surface-water supply is treated Guadalupe River water obtained from the Upper Guadalupe River Authority. Such supply currently is limited by contract to 3,603 acre-feet per year.			
Kerr, City of Ingram			
From Ground-Water Supply	293	376	Trinity Group Aquifer
From Surface-Water Supply	-0-	-0-	None
Total Water Used	293	376	
Note:The water use for the City of Ingram includes water used by residence within and adjacent to the city within the service area of the Ingram Water Supply which is a private water company.			
Travis, Lakeway MUD			
From Ground-Water Supply	-0-	-0-	None
From Surface-Water Supply	767	1,251	Lake Travis
Total Water Used	767	1,251	
Note:The City of Lakeway and some adjacent water users are supplied surface water by the Lakeway Municipal Utility District (MUD) which purchases the water from the Lower Colorado River Authority. Such supply currently is limited by contract to 1,228 acre-feet per year.			
Travis, City of West Lake Hills			
From Ground-Water Supply	-0-	42	Trinity Group Aquifer
From Surface-Water Supply	716	732	Lake Austin
Total Water Used	716	774	
Note:The City of West Lake Hills obtains its main water supply from Lake Austin through the Travis County Water Control and Improvement District No. 10 which purchases treated water from the City of Austin. Ground water from the Trinity Group aquifers is supplied to small portions of the city by wells at Ridgewood Village, the G & J Water District and the Eanes Independent School District.			

Table 18. Projected Water Demands in the Years 1990, 2000, and 2010

Water Demand Category	Projected Water Demand in Acre-Feet (Texas Water Development Board, 1988) 1990	2000	2010
Major Public Supply	15,366	19,580	22,404
Other Public Supply	8,144	11,076	13,734
Subtotal Public Supply	23,510	30,656	36,138
Rural Domestic Supply	6,859	9,328	11,242
Subtotal Drinking Water Demand	30,369	39,984	47,380
Manufacturing	828	1,112	1,416
Power	-0-	-0-	-0-
Mining	24	48	36
Subtotal Industrial Water Demand	852	1,160	1,452
Irrigation	3,413	3,466	3,509
Livestock	4,700	5,349	5,349
Subtotal Agricultural Water Demand	8,113	8,815	8,858
Total Water Demand	**39,334**	**49,959**	**57,690**

Table 19. Projected Water Demands in the Years 1990, 2000, and 2010 for the Selected Major Public Water Systems

County, Water System	Projected Water Demand in Acre-Feet (Texas Water Development Board, 1988) 1990	2000	2010
Major Public Supply	15,366	19,580	22,404
Bandera, City of Bandera	573	848	981
Blanco, City of Blanco	455	623	784
Blanco, City of Johnson City	348	475	597
Gillespie, City of Fredericksburg	2,234	2,731	3,044
Hays, Dripping Springs WSC	363	514	666
Hays, Wimberly WSC	470	622	774
Kendall, City of Boerne	1,227	1,445	1,662
Kendall County WCID #1 (Comfort)	227	259	270
Kerr, City of Kerrville	5,812	7,400	8,548
Kerr, City of Ingram	411	468	499
Travis, Lakeway MUD	2,008	2,537	2,648
Travis, City of West Lake Hills	1,238	1,658	1,931
Total	**15,366**	**19,580**	**22,404**

Table 17 provides the approximate amounts and the sources of water used in 1980 and 1985 by 12 selected major public water supply systems. In 1980, numerous smaller public water supply systems which mainly consist of private water companies, water districts, and water supply corporations used about 2,817 acre-feet of which 1,874 acre-feet was ground water and 943 acre-feet was surface water. Approximately 92 of these smaller public water systems supplied the 1,874 acre-feet of ground water. In 1980, most of these smaller systems using ground water were located in Comal County (41), Kerr County (25), and Kendall County (8). The 943 acre-feet of surface water used in 1980 was supplied by the City of Austin and the Lower Colorado River Authority to such smaller systems in Travis County.

In 1985, such numerous, smaller public water supply systems used about 6,686 acre-feet of which 3,246 acre-feet was ground water and 3,440 acre-feet was surface water. Approximately 120 of these smaller systems supplied the 3,246 acre-feet of ground water. In 1985, most of these smaller systems using ground water were located in Comal County (40), Kerr County (34), Kendall County (10) and Travis County (14). The 3,440 acre-feet of surface water used in 1985 was supplied by the Bexar-Medina-Atascosa Counties WCID No. 1 to a rural residential subdivision in Bandera County (18 acre-feet), and the City of Austin and the Lower Colorado River Authority through local water districts in Travis County (3,422 acre-feet).

In 1980 and 1985, most of the water used for rural domestic supply purposes was estimated to have been provided by numerous small-capacity wells completed in the Cretaceous and Paleozoic aquifers. Some of the water used for rural domestic supplies was provided by some of the public water systems. From 1980 to 1985, water used for rural domestic supplies increased from about 5,007 acre-feet to about 6,256 acre-feet; particularly in Travis, Kendall, Gillespie, Bandera and Hays Counties. All of the water used in 1980 for rural domestic supplies was from ground water. Approximately 4,897 acre-feet was supplied by wells, while 110 acre-feet was ground water supplied by the City of Fredericksburg to rural residences adjacent to the city.

Of the 6,256 acre-feet used in 1985 for rural domestic supplies, 6,203 acre-feet was from ground water and 53 acre-feet was from surface water. Of the 6,203 acre-feet of ground water used, approximately 5,854 acre-feet was supplied by rural domestic wells and approximately 349 acre-feet was supplied to rural residence adjacent to the City of Bandera (29 acre-feet), the City of Johnson City (21 acre-feet), the City of Fredericksburg (269 acre-feet), the City of Boerne (10 acre-feet), and the City of Kerrville (20 acre-feet). The 53 acre-feet of surface water used for rural domestic supplies in 1985 was estimated to have been supplied by the City of Johnson City (22 acre-feet), the City of Blanco (11 acre-feet), and the City of Kerrville (20 acre-feet).

Water use for manufacturing purposes was estimated to be about 620 acre-feet in 1980 and about 286 acre-feet in 1985. In 1980, about 536 acre-feet was supplied from ground water, while 84 acre-feet was supplied from surface water. Of the 536 acre-feet of ground water, 505 acre-feet were supplied by the City of Kerrville and 12 acre-feet were self-supplied by two manufacturing firms; one using 8 acre-feet in Bandera County and one using 4 acre-feet in Kendall County. Of the 84 acre-feet of surface water used in 1980 for manufacturing purposes, one acre-foot was supplied by the City of Johnson City and 83 acre-feet were supplied from local sources (river, creek, pit, etc.) in Gillespie and Kendall Counties.

In 1985, for manufacturing purposes, about 163 acre-feet were supplied from ground water, while 123 acre-feet were supplied from surface water. Of the 163 acre-feet of ground water, 156 acre-feet were supplied by the City of Fredericksburg, 2 acre-feet were supplied by the City of Kerrville and 5 acre-feet were self-supplied by a manufacturing firm in Kendall County. Of the 123 acre-feet of surface water used in 1985, one acre-foot was supplied by the City of Johnson City, 5 acre-feet were supplied by the City Kerrville and 117 acre-feet were supplied from local sources in Gillespie County.

Approximately 121 acre-feet of ground water was used in 1985 for mining purposes in Bandera County (24 acre-feet), Gillespie County (16 acre-feet), and Kerr County (81 acre-feet). There was no water use for mining purposes in 1980, and none used in 1980 and 1985 for steam-electric power generation purposes.

In 1984, approximately 2,650 acres were irrigated (Texas Water Development Board, 1989d). The approximate acreage irrigated by county was as follows: 213 acres in Bandera County, 233 acres in Blanco County, 1,201 acres in Gillespie County, 63 acres in Hays County, 114 acres in Kendall County and 826 acres in Kerr County. The portions of Comal, Medina and Travis counties within the study area were determined not to have any irrigated acreage in 1984. The types of crops irrigated in 1984 included crops for raising of livestock (1,680 acres of grasses, hay, and forage); orchards (517 acres); pecans (201 acres); grains (130 acres); vineyards (80 acres); and vegetables (42 acres). Irrigated acreage in 1984 was somewhat scattered and occurred mostly where there are developed soils in the bottom lands of the Pedernales, Blanco, Guadalupe and Medina Rivers and their tributaries. However, some irrigated lands are found in upland portions of Gillespie and Blanco Counties where soils have developed on the outcrops of the Hickory sandstone and Hensell sand.

In 1980, irrigation water use was about 4,391 acre-feet with about 1,778 acre-feet from ground water and 2,613 acre-feet from surface water. Ninety-two percent of the irrigation water was used in Gillespie County (1,680 acre-feet), Kerr County (1,284 acre-feet), Bandera County (538 acre-feet) and, Kendall County (536 acre-feet). In 1985, irrigation water use was about 3,811 acre-feet with about 2,390 acre-feet from ground water and 1,421 acre-feet from surface water. In 1985, about 80 percent of the irrigation water was used in Gillespie County (1,859 acre-feet) and Kerr County (1,200 acre-feet).

Since the study area has large amounts of land used for grazing, there is a very significant water need for raising livestock. Water used for raising livestock is supplied by numerous wells and local sources of surface water in stock tanks and streams. In 1980, approximately 4,060 acre-feet of water was used for livestock watering. Approximately 2,839 acre-feet of this water was provided by wells and 1,221 acre-feet was provided by local surface-water sources. In 1985, water used for raising livestock was about 3,340 acre-feet with 2,241 acre-feet from ground water and 1,099 acre-feet from surface water. Approximately 84 percent of the water used for livestock watering purposes is used in Gillespie, Blanco, Kendall, Kerr, Hays and Bandera Counties.

Projected Water Demands

The total annual water requirement for the study area is expected to increase by about 90 percent from 1985 through the year 2010. The expected increase is about 130 percent from 1980 through the year 2010. These very large expected increases primarily are due to the large projected population increases previously described. Such population growth will need adequate supplies of suitable quality water for drinking and other household purposes. Water needed for such purposes is expected to increase about 107 percent from 1985 through 2010 and about 196 percent from 1980 through 2010. Water needed for public water supply systems is expected to increase about 117 percent from 1985 through 2010 and about 230 percent from 1980 through 2010. Water needed for rural domestic supply purposes is expected to increase about 80 percent from 1985 through 2010 and about 125 percent from 1980 through 2010.

Slightly larger increases in water uses for manufacturing needs is expected to occur through the year 2010 from about 828 acre-feet in 1990 to about 1,416 acre-feet in 2010. Annual amounts of water needed for mining are expected to be about 24 to 48 acre-feet per year through the year 2010.

Future irrigation water needs are expected to be about 3,413 to 3,509 acre-feet per year during the 1990 through 2010 period. Water for livestock raising is expected to increase about 60 percent from 1985 through the year 2000 and about 14 percent from 1980 through 2000, then level-off at about 5,349 acre-feet per year from 2000 through 2010.

Table 18 provides the projected water demands for the years 1990, 2000, and 2010 by water demand category. The projected water demands for 1990, 2000 and 2010 by county are provided in Appendix F.

The expected water demands for public supply and rural domestic supply are based on population projections and projected high per capita water use with conservation used in the 1988 Texas Water Development Board Revised Data Series. All other projected water demands are based on high series (preliminary draft) projected demands and the apportioned share of total county demands. High series projected water demands are the demands which are likely to occur under a "dry year" condition.

Almost 40 percent of the total high series projected water needs is expected to be required by the 12 major public water supply systems provided in Table 17. Table 19 provides the expected water needs for each of these 12 systems for the years 1990, 2000, and 2010.

The large historical population growth and related historical increases in water used for public supply purposes experienced from 1980 to 1985 and the large projected population growth and related projected public water supply demands expected through the year 2010, strongly indicate a very substantial need for additional and safe drinking water supplies. On a practical basis, sufficient amounts of acceptable quality ground water are not expected to be physically and/or economically available for development to fulfill all or in some cases even part of these large expected additional drinking water demands through the year 2010. This deficiency of acceptable quality ground-water supplies for drinking purposes is expected to be most acute for public water supply systems where the Trinity Group aquifers are the only available source of ground water. Such deficiency of ground water from the Trinity Group aquifers is expected to occur in urbanized areas in parts of Bandera, Blanco, Comal, Hays, Kendall, Kerr, and Travis Counties. Such areas of water supply deficiency will need to acquire additional ground water in remote areas away from current centers of pumpage or surface-water supplies either through permit or purchase to help meet the large expected water needs through the year 2010.

EXPECTED WATER DEVELOPMENT AND GROUND-WATER QUALITY PROBLEMS

Before 1956, apparently all of the existing major public water systems depended entirely on ground water for their water supply. This condition is illustrated by examination of the water use graphs shown in Figure 23. The graph for Blanco indicates that it was the first major public water system to practice conjunctive use of ground water and surface water in 1956. Other major public water systems which initiated such conjunctive use since 1956 are indicated in Figure 23 and include Johnson City in 1967, Boerne in 1979, and Kerrville in 1981.

The development and use of ground water has significant advantages over the development and use of surface water. Ground water can be developed in relatively simple stages by drilling new wells as demand for water increases. Such staged development can be financed in a timely and more cost efficient manner through water user fees rather than large capital investments and loans with interest which are characteristically associated with the development and use of surface water. Ground-water development and use requires only small amounts of land which may be readily retained for other meaningful uses, and requires less maintenance cost because aquifers are natural, in place, relatively permanent sources of water. Also, aquifers have great longevity, are protected by natural overburden from adverse changes caused by the activities of man at the surface, and are not effected by sedimentation which decreases the dependable yield of surface-water reservoirs. Ground water has negligible losses due to evaporation and requires very little treatment. Since aquifers have extensive occurrence and availability of water that is in transit storage, they provide a natural distribution system that minimizes the size of the water distribution system at the land surface (modified from Lehr, 1989). In Texas, ground-water use is an inherent property right and landowners may withdraw as much ground water as physically possible as long as the water is used for beneficial purposes and is not wasted.

Such advantages and benefits from ground-water development and use has been realized by public water systems in the study area for many decades. However, because of the relatively poor hydraulic characteristics of the aquifers, the significantly large expected increases in the demands for water, and the inability or unwillingness of most of the public water systems to adjust to these conditions by obtaining additional lands for the proper spacing of additional wells, only a portion of the ground water available on a sustained basis has been utilized for public water needs.

Fredericksburg is the only major public water system which historically has explored for and successfully developed and used available ground water from the Paleozoic aquifers in areas several miles from the city. This has not been practiced by other major public water systems in the study area. Such public water systems as Kerrville and Boerne have chosen to supplement their ground-water supply from the Trinity Group aquifers with surface water from the Guadalupe River (Kerrville) and Cibolo Creek (Boerne). The City of Blanco used ground water from a local shallow alluvial aquifer until 1956 when it started using surface water from the Blanco River as its main water supply until about 1970. Since 1970, Blanco has used only surface water from the river and has apparently not been able or willing to explore for and develop a supplemental supply from ground water. Johnson City used ground water only up to about 1967 when a supplemental supply was used from the Pedernales River up to 1970. In 1970, Johnson City only used its ground-water supply but then for the next 9 years (1971-1979) only used surface water from the river. In 1980, Johnson City started using ground water again to supplement its surface-water supply, and by 1987 used only ground water from an expanded well field within the city.

Such histories of water development and use along with the limited productivity and performance of the aquifers within limited local areas of concentrated pumpage and the expected public water needs previously presented, indicate the public water supply development problems that can be expected to occur through the year 2010. Additional sustainable amounts of suitable quality ground water will be available for public supply purposes from the Paleozoic and Cretaceous aquifers in remote areas appropriate distances from the current centers of pumpage for public supply use. However, such additional ground water development and use will be costly and will require careful initial assessments and planning, considerable exploration and testing, acquisition of land for production well sites, construction of additional properly spaced production wells, pipelines for delivery of water to the area of use, and in some cases additional ground storage and water treatment facilities.

Currently, there are five major existing surface-water reservoirs within, bordering or adjacent to the study area. These reservoirs include Medina Lake on the Medina River in Medina and Bandera Counties, Canyon Lake on the Guadalupe River in northern Comal County, Lake Travis on the Colorado River in Travis and Burnet Counties and Lake Austin and Town Lake on the Colorado River at Austin in Travis County. Four major water purveyors have permits for use and the sale of surface waters from these five major reservoirs. These four water purveyors include the Bexar-Medina-Atascosa Counties Water Control and Improvement District No. 1 (BMAC WCID No. 1), the Guadalupe-Blanco River Authority (GBRA), the Lower Colorado River Authority (LCRA) and the City of Austin.

The BMAC WCID No. 1 which has about 68,750 acre-feet per year of water permitted from Medina Lake supplies most of its water (about 67,830 acre-feet per year permitted) for irrigation in parts of Bexar, Medina and Atascosa Counties outside of the study area. Currently the BMAC WCID No. 1 has 920 acre-feet per year of water permitted for municipal (public supply) uses. Only about 18 acre-feet of this water for public supply was reported to have been used in 1985 within the study area.

The GBRA which has about 50,000 acre-feet per year of water permitted from Canyon Lake supplies water to municipal (public supply) and industrial water users in the Guadalupe River basin outside the study area. In 1985, only a small, unknown amount of water was supplied from Canyon Lake for local rural domestic supplies adjacent to the lake.

The LCRA has over 2.0 million acre-feet per year of water permitted from Lake Travis for municipal, industrial and irrigation uses. Most of this very large amount of water is supplied for such uses in the large LCRA service area outside of the study area. The only portions of the study area within the LCRA's service area are Blanco County and southwestern Travis County. The City of Austin holds permits for more than 300,000 acre-feet per year of water from Lake Austin (250,000 acre-feet per year permitted), Lake Travis (22,403 acre-feet per year permitted) and Town Lake (36,456 acre-feet per year permitted). These waters are used mainly for municipal and industrial purposes within the Austin water system. A small amount of this water is used for public supply purposes within the Travis County portion of the study area. In 1985, the LCRA and the City of Austin supplied only about 5,405 acre-feet to the Lakeway MUD (1,281 acre-feet) the City of West Lake Hills (732 acre-feet) and other smaller public water systems (3,392 acre-feet) in the Travis County portion of the study area.

One other major surface-water purveyor provides significant amounts of water for public water supply in the study area. The Upper Guadalupe River Authority (UGRA), which serves Kerr County only, holds a 3,603 acre-feet per year permit for water from the Guadalupe River. In 1985, the UGRA supplied about 2,844 acre-feet of treated Guadalupe River water to the City of Kerrville.

Consequently, in 1985 the BMAC WCID No. 1, the GBRA, the LCRA, the City of Austin and the UGRA which have almost 2.5 million acre-feet of annual surface-water rights from the five major reservoirs and the Guadalupe River, only supplied about 8,300 acre-feet of surface water for public water supply purposes in the study area. An explanation of this discrepancy between permitted water rights and actual water supplied to the study area is beyond the scope of this report. However, HDR Engineers, Inc. (1989), addressed the existing and potential surface-water supply problems in their Hays County regional water and wastewater study for the Hays County Water Development Board. HDR's study report addresses in detail the potential alternative water users and suppliers for Hays County and the legal institutional alternatives for delivery of surface waters for future public water use in the county. This report adequately exemplifies the problems related to the future development and use of surface water for public supplies and the conditions and arrangements needed to solve such problems for the remaining portions of the study area; particularly that portion of the study area where the Trinity Group aquifers are the only sources of ground water for public water supply purposes. If feasible, the existing surface-water supplies developed and controlled by the Cities of Kerrville, Johnson City, Blanco and Boerne may be used effectively in an expanded manner for conjunctive use in unincorporated areas within or immediately adjacent to their service areas in Kerr, Blanco and Kendall Counties.

The Cloptin Crossing reservoir, which is proposed in the 1984 Texas Water Plan and is an authorized Corps of Engineers project for construction in Hays and Comal Counties on the Blanco River, would have been a useful water supply for the southeast portion of the study area. However, plans for this reservoir have been dropped (Cross and Bluntzer, 1990). Other potential reservoirs which are included in the 1984 Texas Water Plan and which have been considered as future water supplies include Pedernales reservoir, a proposed Corps of Engineers project on the Pedernales River northwest of Johnson City in Blanco County, and Ingram reservoir, a proposed Upper Guadalupe River Authority project on Johnson Creek northwest of Kerrville in Kerr County. The Dripping Springs reservoir which is a proposed water supply from Onion Creek has been considered in a Hays County water and wastewater study for the Hays County Water Development Board (HDR Engineering, Inc., 1989) as a potential surface-water supply for the Dripping Springs area. If feasible, perhaps these and other proposed reservoirs and surface-water diversions could be used to provide adequate surface-water supplies for future meaningful conjunctive use with appropriately developed ground water in the study area.

Since the Paleozoic and Cretaceous aquifers have very limited amounts of ground-water that can be recovered on a practical basis to meet the large public water supply needs expected to occur through the year 2010, it is imperative that additional amounts of acceptable quality water be developed and utilized. Such additional waters may be made available from the large amounts of surface water known to exist within and immediately adjacent to the study area. The development and use of such surface waters for public water supplies will only be achieved through well planned cooperative arrangements and actions by the existing and potential water purveyors and users within and adjacent to the study area. The area's future public water supply development problems can be and should be appropriately solved through well planned and implemented conjunctive use of ground water and surface water. However, such a solution which involves the development and use of surface water will be very costly and public water users will need to be prepared to make arrangements to adequately address and meet such costs. For this reason, public water systems which currently use ground water should retain this established source of water supply because such supply is in place and can continue to be utilized at some specific sustained level of development at a minimum of cost to water users. On a long-term basis, if sufficient surface-water supplies can not be made available to adequately meet the area's public water supply needs, then additional ground water will have to be developed in remote areas some appropriate distances from existing centers of concentrated pumpage. This additional development of ground waters in remote areas also will be costly.

The ground-water resources have been identified as having moderate to serious water-quality problems related to unusually high to excessive concentrations of nitrate, fluoride, sulfate, alpha radiation and radium. Since public water supply systems are being required to meet EPA primary and secondary drinking water standards, future public water supply wells should be carefully and selectively tested, sampled, and analyzed for various chemical constituents before being developed into production wells. Such water quality testing should definitely include analyses for nitrate, fluoride, sulfate, alpha radiation, and total radium. If unusually high to excessive concentrations of these constituents and radiation are detected, production wells may be properly constructed to avoid them or another safer drinking water supply may have to be developed.

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The Hill Country area addressed in this report covers about 5,539 square miles in all or parts of Bandera, Blanco, Comal, Gillespie, Hays, Kendall, Kerr, Medina, and Travis Counties of central Texas. Within this area, ground-water supplies are obtained from eight aquifers of Paleozoic and Cretaceous ages. The older Paleozoic aquifers include from oldest to youngest the Hickory, the Mid-Cambrian, the Ellenburger-San Saba, and the Marble Falls. The younger Cretaceous aquifers include from oldest to youngest the Lower Trinity, the Middle Trinity, the Upper Trinity, and the Edwards Plateau. Due to stratigrahpic positioning and faulting, these aquifers are hydrologically connected and form leaky aquifer systems in much of the study area. Also, these eight aquifers naturally discharge a significant amount of spring flow, are known to to be hydrologically connected to area streams, and consequently, contribute base flow to effluent reaches of the major rivers and creeks within the study area.

During the 1980's, about 60 percent of the water used in the area was supplied by the eight aquifers. Of the 18,739 acre-feet of ground water used in 1985, about 74 percent was used for drinking and household purposes (public supply and domestic uses).

On an average annual basis the Paleozoic and Cretaceous aquifers are replenished with about 450,000 acre-feet of natural recharge. However, due to the erratic occurrence of ground water and the low coefficients of transmissibility and storage of these aquifers only about 46,000 acre-feet per year can be considered as the sustained yield. Consequently, undesirable water-level declines occur in areas of concentrated withdrawals for public supply purposes where storage has been seriously depleted, pumping lifts increased and well yields greatly reduced.

Unusually high to excessive concentrations of nitrate have been detected in the waters produced from the shallow portions of the aquifers. Nitrate pollution is most evident in the Edwards Plateau aquifer in the western portion of the study area, and appears to be increasing. Such pollution which is believed to be caused by livestock and wildlife excrements (animal wastes) threatens the safe use of the ground water for drinking purposes and the water quality of the base flow to area effluent streams. Inherently high to excessive concentrations of fluoride are found in the water in the deeper portions of the Lower Trinity aquifer. The anhydrite and gypsum beds in the Glen Rose Formation and in some parts of the Travis Peak Formation are the sources of the unusually high to excessive concentrations of sulfate in the waters produced from the Upper and Middle Trinity aquifers. The fluoride and sulfate problems in many cases can be avoided by proper well construction, completion, and development.

The solutions to these ground-water availability and guality problems can be attained by the conjunctive use of ground and surface waters and by the management and protection of the ground-water resources. Such conjunctive use has been and is currently being practiced successfully at Kerrville, Boerne, and Johnson City. Public water systems which should initiate conjunctive use are Bandera, Comfort, Fredericksburg, Ingram, Blanco, Woodcreek, and Wimberly. If conjunctive use is not possible, such public water systems should make earnest attempts to seek additional groundwater supplies in remote areas away from their current wells to avoid undesirable water-level declines and associated depletion of storage, excessive pumping lifts, and reductions in well yields and specific capacities.

Ground-water management and protection could be accomplished by each individual public water system or through a larger governmental entity such as a local or a regional underground water conservation district. In either case, each management and protection entity should establish and maintain: 1) a comprehensive data collection program concerned with the monitoring of water levels, water quality, and pumpage; 2) a program that monitors the effects of ground-water development on the base flow to area streams; 3) a strategic management plan; 4) a well construction, completion, and development program; 5) a pumpage control program; 6) where practical, an artificial recharge program; 7) a water conservation program; 8) a water education program; and 9) where practical, a surface-water acquisition program. Currently, the Hill Country area covered by this report has two local water management and protection entities, namely the Hill Country Underground Water Conservation District which serves Gillespie County and the Springhills Water Management District (a combined surface-water and ground-water conservation district) which serves Bandera County.

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APPENDIX A

Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Constituent Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

(Texas Water Development Board, 1989)

Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Constituent Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significant, Texas Department of Health (1988) Drinking Water Standard Maximum Constituent Level (MCL) and Method of Removal
Aluminum (Al)	Aluminum, the most abundant metallic element, is the third most abundant element in crustal rocks. Aluminum makes up about eight percent of crustal rocks and is dissolved mainly from silicate igneous rocks and from sedimentary rocks consisting predominantly of sandstones and shales. Some of the many minerals having significant amounts of aluminum are bauxite, spinels, feldspars, and corundum. Industrial Uses and Sources: Manufacture and production of building materials, various types of vehicles, cans, bottle tops, foils, frozen food trays, light bulbs, power lines, telephone wires, and many other products. Because of its great abundance, aluminum is present in practically all ground waters and surface waters. The predominant form of aluminum in waters having a pH of less than 4.0 is the metallic aluminum cation (Al +3). At pH of about 4.5 to 6.5 a process of polymerization occurs and various simple to complex forms of aluminum hydroxide, $Al(OH)_2$, polymeric ions are present in solution. At pH of 7.0 or greater the predominant dissolved form of aluminum in solution is the anion $Al(OH)_4$ -1 (another form of aluminum hydroxide). The latter anion occurs usually in relatively small concentrations of 1.0 mg/l or less in most natural waters with ground waters having lesser concentrations than surface waters. Water having a pH of 4.0 or less may have several hundred or several thousand mg/l of aluminum (Al +3 cation) which usually occur in some springs and in acidic drainage waters from mining operations.	Aluminum appears to be an essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is about 0.3 mg/day which is one (1) percent of the average daily intake of 30 mg/day from food, water and air. However, excessive concentrations may be associated with the cause of neurological disorders; namely Alzheimer's disease (encephalopathies), and mental deterioration due to kidney malfunction (dialysis dementia). Excessive concentrations may also cause adult rickets (osteomalacia) by competing with calcium to leave bones soft and susceptible to fracturing. Aluminum is absorbed gastrointestinally, and about 4 percent of intake by humans is retained causing an accumulation with age. MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.
Antimony (Sb)	Antimony, a non-metallic element with chemical traits similar to arsenic, is relatively rare in crustal rocks. It is most abundant in areas of geothermal geysers and in antimonial lead ores. The most important antimonial minerals, is stibnite. Antimony trioxide (Sb_2O_3) is soluble in water while antimony trichloride ($SbCl_3$) is not. The ionic forms of antimony found in water are $2Sb(OH)_2$ +1 cation, $2Sb(OH)_4$ -1 anion, and 2Sb $(OH)_6$ +3 cation. Industrial Uses and Sources: Manufacture and production of hard and strong lead alloys used in electric cables, batteries, and type printing; compounds of antimony are used in the production of plastics, refrigerators, air conditioners, and aerosol sprays. Surface water may have concentrations of about 0.0004 mg/l while drinking waters have about 0.014 mg/l. Some mine drainage waters may have concentrations of 3 to 6 mg/l.	Antimony is a non-essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is about 0.024 mg/day which is about 3.3 percent of the average daily intake of 0.725 mg/day from food, water and air. Antimony is not considered to be cancer causing. However, excessive concentrations can be toxic to the gastrointestinal tract, heart, respiratory tract, skin and liver. The most adverse impact is on the heart. MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.
Arsenic (As)	Arsenic, a non-metallic element, occurs naturally in relatively small amounts in sulfide ore deposits, commonly forming metal arsenides. The most important arsenic mineral is arsenopyrite. When dissolved in water, its stable ionic forms are arsenate (As +5) and arsenite (As+3) oxyanions. From pH of 3 to 7, the dominant anion is H_2As_4 -1. From pH 7 to 11, the dominant anion is $HAsO_4$ -2. The uncharged ion $HAsO_2$ (aqueous) occurs under mildly reducing conditions. Industrial Uses and Sources: Manufacture and production of pesticides, paint pigments, leather, glass, ceramics and metals. The dissolved concentration level of arsenic in natural waters rarely exceeds 0.05 mg/l. Concentrations as high as 5 mg/l have been reported in areas where rocks contain gold ores. A concentration of 40 mg/l has been reported in geothermal waters. Concentrations as high as 362 mg/l have been detected in wastewater effluent from manufacture of some pesticides.	Arsenic is an essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is about 0.003 mg/day which is about 4.6 percent of the average daily intake of 0.065 mg/day from food, water and air. Excessive concentrations of arsenic are poisonous and can cause death, with toxicity varying with form of occurrence. Excessive concentrations can also cause body weight changes, and a decrease in blood hemoglobin as well as promote liver and kidney damage. Primary drinking water standard MCL is 0.05 mg/l. Method of Removal: As +3 and As +6 (if present) by reverse osmosis or distillation; As +5 by ion exchange, activated alumina, adsorption, reverse osmosis, or distillation; and organic arsenic complexes by activated carbon.

Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Constituent Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significant, Texas Department of Health (1988) Drinking Water Standard Maximum Constituent Level (MCL) and Method of Removal
Barium (Ba)	Barium, an alkaline-earth metallic element, is the sixteenth most abundant element in crustal rocks. It is one of the principal elements in barite ($BaSO_4$), a common mineral that occurs in metallic ore veins and in calcite veins in some limestones. Barium is also widely distributed in soils, especially in the western and midwestern U. S. The ionic form of barium in water is the cation Ba +2. Industrial Uses and Sources: Manufacture and production of drilling muds, pain pigments, ceramics, glass, motor oil, detergents and magnets, and is used to purify chemical solutions and as an indicator in x-ray analyses. Median concentrations of barium in most natural waters is approximately 0.045 mg/l, indicating the relatively low solubility of barite in water. High concentrations can be expected in certain oil-field and other brines.	Barium is a non-essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is about 0.083 mg/day which is 10 percent of the average daily intake of about 0.830 mg/day from food, water and air. Its distribution is primarily to bones, and some studies have linked it to elevated blood pressure. Barium is known to contribute to the hardness of water (see hardness as $CaCO_3$). Primary drinking water standard MCL is 1.0 mg/l. Method of Removal: Ion exchange, reverse osmosis or distillation.
Beryllium (Be)	Beryllium, a relatively rare alkaline-earth metallic element, occurs most commonly in beryl and bertrandite which are minerals often associated with pegmatites. The ionic forms of beryllium in equilibrium at pH 6.0 are Be +2 cation, BeOH +1 cation, $Be(OH)_2$ (aqueous) and $Be(OH)_3$ -1 anion. At pH of about 8.5, the Be +2 cation occurs. Industrial Uses and Sources: Manufacture and production of alloys, glass lenses, X-ray tubes, and fluorescent lamps; and is used as a refractory in metal smelting and also as an absorber and conductor of heat in satellites, missiles, rockets and laser technology. Concentrations of beryllium in water are usually very small and usually less than the detection limit of 0.003 mg/l, owing to its low equilibrium solubilities. Concentrations of 1.0 mg/l or more may be regularly detected in acidic (low pH) waters associated with some mining operations.	Beryllium is a non-essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is about 0.001 mg/day which is 8.3 percent of the average daily intake of about 0.012 mg/day from food, water and air. Its adverse effects on humans are unclear. However, some studies have linked it with decreases in growth rate. MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.
Boron (B)	Boron, a non-metallic element, is relatively rare in crustal rocks, but is widely distributed as orthoboric acid (H_3BO_3 and H_2BO_3-1 anion) in volcanic regions, and in evaporites (borates) in some arid lake regions. The most important boron compound is borax which is from the minerals colemanite and kernite which are readily obtained from brine lakes in southern California. Industrial Uses and Sources: Wood and fabric processing; and manufacture and production of detergents, glassware, leather, carpets, cosmetics, photographic supplies, water softeners and rocket and jet fuels. Boron is a minor constituent of most natural waters with concentrations up to only a few tenths of a mg/l. It is found in oil-field brines and the remains of some plants and animals. High concentrations are found in thermal springs in some volcanic areas where concentrations of 48 to 660 mg/l have been detected. Ocean water has a concentration of about 4.6 mg/l. Relatively high concentrations may be present in sewage and industrial waste effluent.	Boron in proper form and concentrations may be vital to human calcium metabolism (see calcium) to help prevent bone deterioration (osteoporosis), and vital to human copper metabolism (see copper) to help main a healthy cardiovascular system. Appropriate daily boron intake by humans has been reported to range from 1 to 3 mg/day from food, water and supplements. The specific intake limit from drinking water is unknown. Excessive amounts greater than 3 mg/day taken orally from food, water and supplements may be dangerous; adversely effecting human calcium and copper metabolisms. Another investigation of boron indicated that under conditions of low dietary magnesium, dietary boron may influence the brain function of healthy adult men and women. Boron in small concentrations is essential for plant growth. However, high excessive concentrations in soils and irrigation waters are harmful to plants; depending on the type of plant and the concentration of boron. Concentrations as high as 1.0 mg/l are permissible for irrigation of sensitive crops such as fruit trees (lemon, orange, peach, etc.), nut trees (pecans, etc.) and navy beans. Concentrations as high as 2.0 mg/l are permissible on semi-tolerant crops such as most grains, cotton, potatoes, and some other vegetables. Concentrations as high as 3.0 mg/l are permissible on tolerant crops such as alfalfa, and most root vegetables. The most serious hazard posed by boron to the environment (air and perhaps water) is through boranes which are highly toxic compounds used as fuels for rocket motors and jet engines. MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.

Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Constituent Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significant, Texas Department of Health (1988) Drinking Water Standard Maximum Constituent Level (MCL) and Method of Removal
Bromide (Br)	Bromine, a relatively rare non-metallic, halogen group element, is similar in chemical behavior to chlorine and in natural waters is always present as the bromide anion Br -1. Its main sources are from sodium, potassium and magnesium bromide salts found in sedimentary rocks such as evaporites, carbonates and shales. Industrial Uses and Sources: Manufacture and production of ethylene dibromide (a gasoline additive), fumigants, fire-retardant agents, pesticides and medicines. Concentrations in most natural waters range from about 0.005 to 0.15 mg/l. Geothermal waters may have concentrations greater tan 20 mg/l. Concentrations of up to 3,720 mg/l are found in some brines.	The beneficial or hazardous significance of bromide concentrations in waters used for drinking, industrial or irrigation purposes is unknown. The presence of small amounts of bromide in fresh water probably is not of any ecologic significance. The introduction of bromine to the environment by human activities in urban areas is probably significant. MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.
Cadmium (Cd)	Cadmium, which is chemically similar to zinc, is a relatively rare metallic element, and occurs in the mineral greenockite and as a secondary constituent in zinc ores such as sphalerite and some copper ores. The simple ionic forms found in ground waters are the Cd +2 cation at pH less than 8.0, and Cd (OH) (aqueous) and the Cd $(OH)_3$ -1 anion at high pH. Industrial Uses and Sources: Electroplating and manufacture and production of pigments, printing ink, plastics and batteries. Cadmium is relatively insoluble in water, rarely occurring in concentrations over 0.01 mg/l. Excessive concentrations may be detected in acidic (low pH) waters associated with some mining operations.	Cadmium is a non-essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is about 0.001 mg/day which is 2.9 percent of the average daily intake of 0.035 mg/day from food, water and air. Excessive concentrations in water accumulate in the kidney and liver and may cause kidney damage and abnormal presence of protein, sugar and amino acid in the urine. Cadmium is also known to cause lung and prostate cancer when inhaled. Primary drinking water standard MCL is 0.01 mg/l. This concentration is also the upper limit for irrigation waters, because cadmium is known to accumulate in and be toxic to plants. Method of Removal: Distillation, reverse osmosis or ion exchange.
Calcium (Ca) and Magnesium (Mg)	Calcium and magnesium are alkaline-earth metallic elements and are readily dissolved from practically all soils and rocks. Calcium, the fifth most abundant element in crustal rocks, makes-up about 3.5 percent of crustal rocks and is the most abundant alkaline-earth metallic element. It is mostly derived from such minerals as amphiboles, feldspars, gypsum, pyroxene, aragonite, calcite, dolomite and clay minerals. The ionic forms of calcium are the cations Ca +2 and $CaHCO_3$+1. Magnesium, the eighth most abundant element in crustal rocks, is derived from such minerals as a amphiboles, olivine, pyroxenes, dolomite, magnetite and clay minerals. Magnesium occurs in solutions as the cation Mg +2, but readily precipitates as the mineral brucite, $Mg(OH)_2$. Industrial Uses and Sources: Calcium is used in the manufacture and production of alloys, leather, petroleum, cement, plaster, fertilizers and paint; while magnesium is used for the manufacture and production of alloys, aircraft and automobile parts, tools and other equipment, anodes, fireworks, flares, incendiary bombs, medicines, and protective coatings. Calcium and sodium are usually the dominant cations in natural waters. Magnesium is not a dominant cation in most natural waters because its chemical behavior is very different from that of calcium and sodium. Consequently, in most natural waters, the magnesium concentration is much lower than the calcium or sodium. Calcium and magnesium are found in large quantities in some brines. Magnesium is present in large quantities in sea water with concentrations exceeding 1,000 mg/l.	Calcium and magnesium are essential elements for human metabolic needs and for plant nutrition. Drinking waters account for about 25 percent of the average daily intake of calcium by an adult human and for about 3 percent of the average daily intake of magnesium by an adult human. A deficiency of calcium may result in bone deterioration (osteoporosis) while an excess may cause kidney stones. A deficiency of magnesium may result in an electrolyte imbalance, while an excess may cause muscle weakness. High concentrations of magnesium have a laxative effect, especially on new users of the water supply. Calcium and magnesium combine with carbonate, bicarbonate, sulfate, and silica to form heat-retarding, pipe-clogging scale in boilers, water heaters, cooking utensils, and other hot water using appliances and heating utensils, and other hot, water using appliances and heating exchange equipment. Calcium and magnesium are soap consuming (see hardness as $CaCO_3$). Low concentrations are desirable for electroplating, tanning, dyeing, and textile manufacturing. Method of Removal: Distillation, reverse osmosis or ion exchange.

Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Constituent Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significant, Texas Department of Health (1988) Drinking Water Standard Maximum Constituent Level (MCL) and Method of Removal
Carbonate (CO_3) and Bicarbonate (HCO_3)	The carbonate (CO_3 -2) and bicarbonate (HCO_3 -1) anions result from the reaction of carbon dioxide (CO_2) with water and carbonate rocks such as limestone and dolomite. Also the hydrolysis of calcite ($CaCO_3$) with water forms bicarbonate (HCO_3-1). The carbonate and bicarbonate anions and carbon dioxide influence water acidity and alkalinity. Carbonate is usually only present in natural waters when the pH exceeds 8.3. In ground waters, the carbonate concentration is commonly less than 10 mg/l, while the bicarbonate concentration is commonly less than 500 mg/l, but may exceed 1,000 mg/l in water that is highly charged with carbon dioxide (CO_2).	Carbonate and bicarbonate produce alkalinity. Bicarbonates of calcium and magnesium decompose in steam boilers and hot water facilities to form scale and release corrosive carbon dioxide gas. In combination with calcium and magnesium, they cause carbonate hardness (see hardness as $CaCO_3$). MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.
Chloride (Cl)	Chlorine, a relatively abundant non-metallic halogen group element, is present in wagers as the anion chloride (Cl -1). It is dissolved mainly from the mineral halite (NaCl) or common rock salt found in sedimentary rocks and soils. Chloride is present in sewage and found in large amounts in oil-field brines, sea water and industrial brine effluent. Industrial Uses and Sources: Chlorine is used to purify drinking water, kill bacteria in wastes, and in the manufacture and production of herbicides, pesticides, drugs, dyes, metals and plastic; while chloride compounds are used in photography, preservatives, medical products, electroplating and soldering. Chloride is present in all natural waters. Concentrations are usually low in fresh surface waters and slightly higher in fresh ground waters with concentrations usually less than 300 mg/l. Concentration in sea water is about 19,000 mg/l. Concentration in some brines can be as much as 190,000 mg/l.	Chloride is essential for human metabolic needs. A deficiency may result in increased alkalinity of the blood which may cause hypochloremic alkalosis. Excessive chloride may result in decreased alkalinity of the blood which may cause hyperkalemic metabolic acidosis. Chloride concentrations in excess of 100 mg/l in combination with sodium imparts the salty taste to drinking water. The average daily intake by an adult human from drinking waters is less than 84 mg/day and is less than one (1) percent of the average daily intake of 8,440 mg/day from food, water and air. In large quantities, chloride increases the corrosiveness of water. Food processing industries usually require less than a 250 mg/l concentration. Secondary drinking water standard MCL is 300 mg/l. Method of Removal: Distillation, reverse osmosis or ion exchange.
Chromium (Cr)	Chromium, a relatively rare transition metallic element, occurs most frequently in nature in ultramafic igneous rocks and in lathyritic soils that overlie ultramafic igneous rocks. The most important chromium mineral is chromite. Dissolved chromium may be present in water as trivalent cations Cr +3, or as anions in which the oxidation state is Cr +6. Industrial Uses and Sources: Manufacture and production of alloys, plated metals, electric heating elements, leather, paint, dyes, anodes and cement. Concentrations of chromium in natural waters are commonly less than 0.01 mg/l. A concentration of 14 mg/l has been detected in ground water contaminated by industrial effluent. Concentrations of 0.1 to 0.2 mg/l have been detected in ground water contained in rocks having chromium minerals.	Chromium is an essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is about 0.016 mg/day which is 13 percent of the average daily intake of 0.12 mg/day from food, water and air. A deficiency of chromium may result in degeneration of blood vessels (atherosclerosis). The toxicity of chromium may include loss of kidney tissue (tubular necrosis). It appears not to be cancer causing. Primary drinking water standard MCL is 0.05 mg/l. Method of Removal: Distillation, reverse osmosis or ion exchange; and activated carbon for organic chromium compounds.
Cobalt (Co)	Stable (non-radioactive) cobalt, a relatively rare transition metallic element, is found mostly in igneous rocks and shales, and occurs in such minerals as cobaltite and cobaltomenite which are usually associated with pyrite. Stable cobalt is found in oxide, carbonate, chloride, hydroxide, nitrate and sulfate forms. The common ionic form found in ground water is the Co +2 cation. Stable cobalt also occurs in other complex ionic forms in water. Industrial Uses and Sources: Manufacture and production of alloys for high speed cutting tools and surgical instruments and as a catalyst. Radioactive cobalt is found in 18 isotope forms. In natural waters stable cobalt usually occurs in very low concentrations of less than 0.001 mg/l which usually cannot be detected. Concentration in sea water, is probably about 0.00003 mg/l. Concentration in water within and near mineralized zones has been detected at about 0.02 mg/l.	Stable (non-radioactive) cobalt is an essential element for human metabolic needs. The average daily intake by an adult human for stable cobalt is 3.5 mg/day from food, water, and air. The specific amount from drinking water is unknown. A deficiency of stable cobalt may result in anemia. Excessive oral intake of stable cobalt may adversely impact the nervous system, testes, blood, heart and thyroid. MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.

Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Constituent Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significant, Texas Department of Health (1988) Drinking Water Standard Maximum Constituent Level (MCL) and Method of Removal
Copper (Cu)	Copper, a moderately abundant metallic element, occurs in crustal rocks as free native metal, and in such copper minerals as chalcocite, bornite, cuprite, malachite, and azurite. Copper forms rather stable sulfide ore minerals, which also sometimes contain iron. Copper commonly occurs in water as Cu +2 or Cu +1 cation forms. Above pH 7.0, the dominant form may be the anion $Cu(OH)_3$ -1. Aerated water with carbon dioxide may have $CuCO_3$ (aqueous) as the dominant uncharged ion. Industrial Uses and Sources: Manufacture and production of various types of wire, superconductors, electroplating solutions, electronic and electrical parts, chemical etching solutions, pesticides and many other products. Copper may be present in concentrations as great as a few hundred mg/l in acidic (low pH) drainage waters from copper mines. Natural waters usually contain less than 0.01 mg/l.	Copper is an essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is about 0.2 mg/day which is 12 percent of the average daily intake of 1.7 mg/day from food, water and air. A deficiency may result in anemia, loss of pigment in the skin, reduced growth and loss of arterial elasticity. Toxicity may include Wilson's disease (damage to the brain, eyes, kidney, and liver) for susceptible persons, and liver disorder (hepatic cirrhosis). Secondary drinking water standard MCL is 1.0 mg/l. Method of Removal: Ion exchange, reverse osmosis or distillation.
Cyanide (CN)	Cyanide is a synthetic organic substance commercially made on a large scale by reacting methane gas (CH_4) with the ammonium cation (NH_4+1) to form hydrogen cyanide (HCN) which occurs as a liquid at 25.6°C and readily hydrolyzes in water. The ionic form of cyanide is the CN -1 anion which forms stable complex compounds with most metals. Industrial Uses and Sources: Production of methyl methacrylate, acidic acid, nylon, gold from gold ores, and fertilizers. The average concentration in drinking water has been determined to be 0.00009 mg/l.	Cyanide is a non-essential constituent for human metabolic needs. The average daily intake by an adult human has been estimated to be 0.00009 mg/l. Free compounds of cyanide are readily absorbed through the gastrointestinal tract and lung. Cyanide is distributed to the blood, lung, liver and kidney. Excessive concentrations in water may result in hyperventilation, vomiting, unconsciousness, convulsions, rapid and irregular heart rate, vascular collapse and death. EPA's "no observed adverse effect levels" for various cyanide compounds are given on page 237 of Lappenbusch, 1988,, and range from 0.020 mg/l for hydrogen cyanide to 0.200 mg/l for phosphorus-silver cyanide. Method of Removal: Alkaline chlorination, electrolytic decomposition, ozone oxidation or ion exchange.
Fluoride (F)	Fluorine, a moderately abundant non-metallic halogen group element, is present in waters as the anion fluoride (F -1). It is dissolved in small to very small quantities from such minerals as fluorite, amphiboles, apatite, and mica. Fluoride minerals are most commonly found in carbonate rocks, volcanic rocks or sedimentary rocks derived from volcanic rocks. Industrial Uses and Sources: Manufacture and production of glass, steel, aluminum, pesticides, and fertilizers, and used in electroplating. Concentrations of fluoride in natural waters generally do not exceed 10 mg/l in ground waters or 1.0 mg/l in surface waters. The concentration of fluoride may be as much as 1,600 mg/l in some brines. Fluoride is added to many public drinking waters by fluoridation.	Fluoride is an essential constituent for human metabolic needs. The estimated average daily intake of fluoride by an adult human is about 1.7 mg/day from food, water, and air. About one-half (0.85 mg/day) of this is probably from drinking waters. Fluoride concentrations between 0.6 and 1.7 mg/l in drinking water have a beneficial effect on the structure and resistance to decay of children's teeth. A deficiency may result in weakening of bone (osteoporosis). Certain but unknown concentrations of unusually high fluoride may be beneficial for the prevention of hardening of the arteries. Excessive fluoride may cause mottling of teeth and abnormal bone thickening and hardening (osteosclerosis) depending on the concentration, age of the individual, amount of water ingested, and susceptibility of the individual. Primary drinking water standard MCL is 4.0 mg/l. Secondary drinking water standard MCL is 2.0 mg/l. Method of Removal: Distillation, reverse osmosis, ion exchange or lime softening.
Gross Alpha	Alpha radiation consists of the emission of positively charged helium nuclei from the nucleus of atoms having high molecular weight. When an alpha particle is emitted from an atom, the atomic weight of the atom decreases by four (4) units. This is called radioactive decay or disintegration and is measured and reported in water analyses as gross alpha in picocuries per liter (pCi/l). Alpha-emitting isotopes in natural waters are mainly isotopes of radium and radon (see radium and radon) which are members of the uranium and thorium disintegration	The release of energy from an atom of a radioactive substance is called ionizing radiation. Alpha particles which are subatomic particles and one of the forms of ionizing radiation are relatively slow-moving, but carry a strong positive charge with energy levels so high that when they collide with an atom or molecule of other substances, they strip away an electron; thus altering or ionizing the substance. Alpha particle radiation cannot penetrate a piece of paper or human skin, but is very dangerous when the radioactive substance emitting them is contained in

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Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Constituent Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significant, Texas Department of Health (1988) Drinking Water Standard Maximum Constituent Level (MCL) and Method of Removal
Gross Alpha *(continued)*	series. Natural waters having high gross alpha concentrations usually occur in deep aquifers or in areas effected by uranium or phosphate mining. Most natural ground waters in Texas probably have gross alpha concentrations of less than 5 pCi/l. Ground waters produced from the Hickory aquifer in central Texas commonly have gross alpha concentrations greater than 15 pCi/l, and may have very high levels as much as 50 to 75 pCi/l.	ingested water and food or in inhaled air. Therefore, alpha particles emitting from radioactive substances ingested or inhaled are most harmful to living tissues of human internal organs by altering or destroying the atoms and molecules of such tissues. The amount of alteration or destruction of the tissues depends on where and how long the tissues were exposed to the radiation and the dosage of the radiation. Under these varying circumstances and conditions, the organ having the effected tissue may repair itself of the damage or may develop cancerous cells and tumors. In some instances, certain ionizing radiation is used to advantage by pinpointing certain cancers in human tissue, bombarding them with heavy-ion radiation, destroying them and prolonging life. The primary drinking water standard MCL for gross alpha radiation is 15 pCi/l. Method of Removal: By the methods used to remove the radioactive substance emitting the radiation (see "Method of Removal" for radium, radon, and uranium).
Gross Beta	Beta radiation consists of the emission of high energy electrons or positrons from the nucleus of atoms having high molecular weight. During the production of a beta particle, the neutron of the atom is converted to a proton and an electron is emitted as the beta particle. When a beta particle is emitted from an atom, the atomic number of the atom increases one (1) unit. This beta particle decay or disintegration is measured and reported in water analyses as gross beta in picocuries per liter (pCi/l). Natural beta-emitting isotopes are those in the uranium and thorium disintegration series, and also from potassium-40 and rubidium-87. Strong beta emitting isotopes from nuclear fission which are important in water chemistry are strontium-89, strontium-90, iodine-131, phosphorus-32 and cobalt-60. High gross beta concentrations greater than 50 pCi/l have been detected in ground waters from the Gulf Coast aquifer in southeastern Texas.	The release of energy from an atom of a radioactive substance is called ionizing radiation. Beta particles which are subatomic particles and one of the forms of ionizing radiation are extremely fast-moving electrons (negatively charged) and positrons (positively charged) which have extremely high energy levels. When beta particles collide with an atom or molecule of other substances they alter or ionize the substance. Beta particle radiation is capable of penetrating several millimeters of human skin, and like alpha particle radiation, it can be harmful when emitted inside the human body (see corresponding paragraph or alpha particle radiation). Positrons emitted as beta particles can combine with free electrons to produce gamma ray radiation which has great penetrating power and is capable of passing easily into the human body causing damage to tissue in the process. The primary drinking standard MCL for gross beta radiation is 50 pCi/l;. Method of Removal: By the methods used to remove the radioactive substance emitting the radiation (see "Method of Removal" for radium, radon, and thorium).
Iodide **(I)** **and Idodate** **(IO_3)**	Stable (non-radioactive) iodine, a relatively rare non-metallic halogen group element, is present in water as the iodide anion (I -1) and iodate anion (IO_3 -1). These forms are widely distributed with their circulation being strongly influenced by plant absorption. Calcium and sodium iodate salts which are known to occur in some caliche-type saltpeter (sodium nitrate) deposits may be important sources of iodine concentrations in some ground waters. Industrial Uses and Sources: Iodine is used in chemical analyses, while iodine compounds are used in making photographic film, antiseptics and as an additive to table salt. Concentrations in natural waters probably rarely exceed 0.04 mg/l, while sea water has about 0.06 mg/l and some brines contain as much as 50 mg/l.	Iodine is an essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is about 0.010 mg/day from food, water and air. A deficiency may result in an enlarged thyroid gland (goiter). However, excessive concentrations may cause goiter and overactivity of the thyroid gland (hypothyroidism). MCL has not been determined. Method of Removal: Activated carbon.
Iron **(Fe)**	Iron is the second most abundant metallic element in crustal rocks. Iron is present in numerous igneous rock minerals, and is usually reprecipitated quickly after being released by weathering, commonly forming cement in sedimentary rocks. The most important iron ore minerals are hematite, geothitelimonite, magnetite and siderite. Industrial Uses and Sources: Production of steel for a wide variety of products related mainly to transportation, shipping, and construction,	Iron is an essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is 0.6 mg/day which is only 3 percent of the average daily intake of 20 mg/day from food, water and air. A deficiency of iron in the body may result in iron deficiency anemia (a hypochromic anemia). Intake of excessive concentrations may cause gastrointestinal irrigation. Oral intake of highly excessive concentrations of iron are known to cause iron deposition in

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Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Constituent Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significant, Texas Department of Health (1988) Drinking Water Standard Maximum Constituent Level (MCL) and Method of Removal
Iron **(Fe)** ***(continued)***	and iron compounds used to make dyes, inks, disinfectants, paints and polishing power. The occurrence of iron in water is also commonly influenced by micro-organisms that metabolize it in the biosphere. The most common form of iron in solution in ground water is the ferrous ion (Fe +2 cation). In alkaline waters with pH above 9.5, the anions, Fe(OH) -1, $FeOH_3$ -1 or $HFeO_2$ -2, can exist in significant concentrations. The ionic forms of iron that exist in acidic (low pH) water are the cations Fe +3 (ferric iron), FeOH +2, and $Fe(OH)_2$ +1; the $Fe(OH)_3$ (aqueous), uncharged ion; the rare cation $Fe_2(OH)_2$ +1; and the $Fe(OH)_4$ -1 anion. In water, iron can also form complex ions with chloride, fluoride, sulfate and phosphate. Concentrations of iron in most natural waters is usually very small at less than 0.3 mg/l. However in some areas, concentrations of 1.0 to 10 mg/l of iron are common. Ground waters with pH between 6 and 8 may contain as much as 50 mg/l ferrous iron. Some ground waters with very low pH have extremely high concentrations. Ground water movement through rocks containing oxidized iron minerals and organic debris, provide favorable sources for iron in ground waters. High iron concentrations in water may be derived from well castings, pipes, pumps, storage tanks, and other cast iron and steel water delivery facilities and equipment.	the skin and such vital organs as the heart, pancreas, liver and kidney, with serious impairment of their functions (hemochromatosis). Iron is an essential element in the metabolism of plants. More than about 0.3 mg/l of iron in water will stain laundry and utensils reddish-brown, cause unpleasant taste, and favor growth of iron bacteria. More than 0.2 mg/l is objectionable for most industrial uses of the water. Secondary drinking water standard MCL is 0.3 mg/l. Method of Removal: Ion exchange and reverse osmosis for the ferric ion, and distillation and filtration or chlorination and precipitation for the ferrous ion.
Lead **(Pb)**	Stable (non-radioactive) lead, a relatively rare metallic element, is rather widely dispersed in igneous rocks and sedimentary rocks such as shales and carbonates. The main source is from such minerals as galena, cerussite and anglesite. The principal ionic forms of lead in ground water are the Pb +2 cation and other complex ions of lead hydroxide, lead sulfate and lead carbonate. Industrial Uses and Sources: Manufacture and production of storage batteries, tetraethyl lead (gasoline additive), paints, dyes, and alloys for pipes and tanks, and shields against radiation. The radioactive beta-emitting isotope, lead-210, is produced in the decay series of uranium-238, has a 21.4 year half-life and has been used as a tracer in hydrologic studies. The natural mobility of stable lead is low because of the low solubility of lead hydroxy carbonates; therefore, concentrations in natural waters rarely exceed 0.01 mg/l. Concentrations in rain and snow have been detected at 0.1 mg/l or more in areas having air pollution, and at 0.001 mg/l or more in remote areas. Surface waters sampled in the northeastern and southeastern U.S. had lead concentrations generally greater than 0.001 mg/l while those sampled in the western U. S. had concentrations less than 0.001 mg/l.	Lead is a non-essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is about 0.015 mg/day which is about 30 percent of the average daily intake of 0.050 mg/day from food, water, and air. Excessive concentrations of lead are known to cause irreversible brain damage when lead concentrations in the blood exceed 100 to 120 micrograms per deciliter. Less severe adverse effects, including physiological disturbances of several organ systems, can be expected at lower excessive levels. Primary drinking water standard MCL is 0.05 mg/l. Method of Removal: Reverse osmosis, distillation or flotation - sedimentation- filtration.
Manganese **(Mn)**	Manganese is the fourth most abundant metallic element in crustal rocks. Many igneous and metamorphic rocks contain manganese as a minor constituent, and small amounts of manganese are also present in such sedimentary rocks as dolomite and some limestones, substituting for calcium. The main source is from such minerals as franklinite, pyrolusite, manganite and rhodochrosite. In aqueous solution, divalent manganese (Mn +2 cation) commonly precipitates to form coatings of manganese oxide (desert varnish). The ionic forms of manganese in ground water are the cations Mn +2, Mn +3, and Mn +4 with Mn +2 and Mn +4 being the most common. Complex ions of manganese hydroxide and manganese bicarbonate may also be present in waters.	Manganese is an essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is about 0.086 mg/day which is only 2 percent of the average daily intake of about 4.3 mg/day from food, water, and air. A deficiency may result in decreased enzymatic reactions in carbohydrate metabolism, organic acids. Adverse effects from excessive concentrations may include neuro behavioral changes, anemia and muscle cramps. Secondary drinking water standard MCL is 0.05 mg/l. Method of Removal: Filtration (oxidizing filters), ion exchange, reverse osmosis, distillation or chlorination and precipitation.

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Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Constituent Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significant, Texas Department of Health (1988) Drinking Water Standard Maximum Constituent Level (MCL) and Method of Removal
Manganese (Mn) *(continued)*	Industrial Uses and Sources: Manufacture and production of alloys, batteries, paint, glass, flares and fireworks. Concentrations of manganese in natural waters are usually small, with exceptions above 1.0 mg/l occurring around some thermal springs and in brines.	
Mercury (Hg)	Mercury, a metallic element, and mercury ore (the mineral cinnabar) are rare in crustal rocks and not widely dispersed. The most common ionic form of mercuty in ground water is the cation Hg +2. It also can occur as the complex organic cation $HgCH_3$ +1 (methyl mercury). Industrial Uses and Sources: Manufacture and production of organic pesticides, explosives, batteries, photographic supplies, scientific instruments, paints, pharmaceuticals, paper and pulp, and catalysts. Mercury compounds are emitted during the combustion of coal and oil. Concentrations of mercury in natural waters are usually less than 0.002 mg/l, with exceptions occurring near cinnabar mines and around industrial sites where the element is used for various purposes.	Mercury is a non-essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is only 0.002 mg/day which is about 30 percent of the average daily intake from food, water and air. Any measurable concentration from drinking water is undesirable. Adverse effects from excessive concentrations of mercury may include kidney damage and abnormal presence of protein in the urine. Also, ethyl mercury, adversely affects the nervous system. Primary drinking water standard MCL is 0.002 mg/l. Method of Removal: Reverse osmosis or distillation.
Molybdenum (Mo)	Molybdenum is a relatively rare transition metallic element found most commonly in the minerals molybdenite and wulfenite. In oxidizing environments, the dominant ionic form of molybdenum is Mo +6. In waters having a pH greater than 5.0 the dominant form is the anion MoO_4 -2. Industrial Uses and Sources: Manufacture and production of alloys, wire, lubricants, electrical parts, fire proofing fabrics, and in the dyeing of leather, silk and wool. Most natural waters contain less than 0.001 mg/l. Concentrations as much as 3.8 mg/l have been detected in waters effected by molybdenum mining operations.	Molybdenum is an essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is about 0.011 mg/day which is about 3 percent of the average daily intake of 0.35 mg/day from food, water and air. A deficiency may result in reduced quantities of metallo-enzymes. Adverse effects from excessive concentrations include liver, kidney, spleen, and adrenal damage. At some natural, excessive concentrations, toxicity may include elevated uric acid resulting in gout and bone and joint deformities. MCL has not been determined. Method of Removal: Ion exchange, reverse osmosis or distillation.
Nickel (Ni)	Nickel is a relatively rare transition metallic element in crustal rocks that sometimes substitutes for iron in ferromagnesian igneous-rock minerals, and which tends to precipitate with iron and manganese oxides. Nickel is mined with ferrous sulfide ores and nickel-bearing ores developed on ultramafic bedrock, terrances. Important nickel-bearing minerals include niccolite, millerite, pentlandite and garnierite. The ionic forms of nickel in ground water are the cations Ni +2, Ni +3, and Ni +4. Industrial Uses and Sources: Manufacture and production of alloys, scientific instruments, pendulums, steel tapes, coins, electrical parts, propellers, acid pumps, valves and plated metals. A median concentration of 0.01 mg/l is estimated for natural waters. Concentrations of about 0.04 mg/l have been detected in waters in some mineralized regions.	The importance of nickel for human metabolic needs is unknown. The average daily intake by an adult human from drinking waters is not specifically known, but the average daily intake is about 0.34 mg/day from food, water, and air. Toxicity may include gastrointestinal irrigation and an inflammation of the skin (dermatitis). Nickel is cancer causing when inhaled but not when ingested. MCL has not been determined. Method of Removal: Ion exchange, reverse osmosis or distillation.
Nitrate (NO_3) or Nitrate as Nitrogen (N)	The main source for the occurrence of nitrogen in ground water are decaying organic matter, human and animal wastes, fertilizers, and the minerals soda niter (sodium nitrate) and niter (potassium nitrate) found in rocks and soils. Nitrogen ionic forms that occur in ground water are the anions NO_3 -2 (nitrate), and NO_2 -2 (nitrite) and the cation NH_4 +1 (ammonium). The nitrate anion (NO_3-2) is the ionic form most commonly detected in ground water. The nitrite and ammonium ions are generally unstable in ground water and are usually not detectable. Another nitrogen ionic form is the cyanide anion CN -1 (see cyanide) which may be found in ground water contaminated by some wastewater effluents. Concentrations of	Nitrate is a non-essential constituent for human metabolic needs. The average daily intake by an adult human from drinking waters is about 20 mg/day which is about 13 percent of the average daily intake from food, water and air. Nitrate concentrations in water which are significantly greater than the local average may suggest pollution. Water having excessively high nitrate concentration have been reported to be the cause of methemoglobinemia (an often fatal disease in infants); therefore such water should not be used for infant feeding. Excessive concentrations of nitrate may be a cancer precursor. Nitrate is helpful in reducing intercrystaline cracking of boiler steel. It encourages growth of algae and other organisms which

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Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Constituent Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significant, Texas Department of Health (1988) Drinking Water Standard Maximum Constituent Level (MCL) and Method of Removal
Nitrate (NO_3) or Nitrate as Nitrogen (N) ***(continued)***	nitrate in natural waters usually are very small when not influenced by sewage or ranching and farming activities. Some areas with rocks and soils having significant amounts of nitrate minerals, can have associated waters with unusually high natural concentrations of nitrate.	produce undesirable tastes and odors. Primary drinking water standard for nitrate (NO_3) is 44.3 mg/l. Primary drinking water standard for nitrate as nitrogen (N) is 10 mg/l. Method of Removal: Distillation, reverse osmosis or ion exchange.
Phosphate (PO_4)	Phosphorus is a moderately abundant non-metallic element in igneous rocks, occurring in apatite and other phosphate minerals. It is also moderately abundant as phosphate minerals in some limestones, sandstones and shales. Industrial Uses and Sources: Manufacture and production of phosphoric acid detergents, fertilizers, munitions and superphosphate. Phosphate ionic forms in water include H_3PO_4 (aqueous), H_2PO_4 -1, HPO_4 -2, and PO_4 -3. The ionic form present is dependent on the pH of the water. The anions H_2PO_4 -1 and HPO_4 -2 are present in ground waters having pH of 5.0 to 9.2. Concentrations of phosphate in natural waters are normally no more than a few tenths of a mg/l owing to the low solubility of most of its inorganic compounds and its use by biota as a nutrient. Phosphate is a common component of sewage and is always present in animal waste.	Phosphate is an essential constituent for human metabolic needs, and is used as a nutrient by animals and plants. The average daily intake by an adult human from drinking waters is probably less than 15 mg/day and is less than one (1) percent of the average daily intake of 1,500 mg/day from food, water, and air. A deficiency of phosphate may result in weakness, bone pain and rickets. Adverse effects from excessive concentrations may include gastrointestinal irritation, and kidney and liver damage. MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.
Radium (Ra)	Radium, an alkaline-earth metallic element that behaves chemically somewhat like barium, is strongly radioactive with four naturally occurring isotopes; namely radium-223, radium-224, radium-226, and radium-228. The dominant isotopes found and detected in natural waters are radium-226 which is a disintegration product of uranium-238, and radium-228 which is a disintegration product of thorium-232. This disintegration or radioactive decay is spontaneous and causes radium-226 to disintegrate to radon-222 (see radon) by the release of beta particles. Radium is derived from igneous rocks such as granites, uranium ore bodies, certain shales and sandstones, and volcanic tuffs. The ionic forms of radium are the cation Ra +2 and $RaSO_4$ complex ions. Radium is used in the treatment of cancer and other diseases, as an eluminant, and for the detection of flaws in steel. In water analyses radium concentrations are measured and reported in picocuries per liter (pCi/l). The total radium concentration for most water analyses is the sum of radium-226 and radium-228 in pCi/l. The concentration of total radium in most natural waters is usually less than 1.0 pCi/l. The population-weighted averages of radium-226 and radium-228 in U. S. community water supplies were determined to be 0.5 and 0.6 pCi/l, respectively. EPA determined population-weighted ranges of 0.3 to 0.8 pCi/l for radium-226 and 0.4 to 1.0 pCi/l for radium 228 in community water supplies. Analyses of fresh ground waters produced from the Hickory aquifer around the Llano uplift of central Texas indicate unusually high total radium concentrations that may be three to four times greater than 5.0 pCi/l. Concentration in some brines has been detected as high as 720 pCi/l.	Radium is not known to have any essential function for human metabolic needs. Radium is known to replace calcium in bone. Excessive concentrations of radium in water may cause bone and bone marrow cancers in humans. Primary drinking water standard MCL for total radium (radium-226 plus radium-228) is 5 pCi/l. Method of Removal: Ion exchange, reverse osmosis or oxidation and reduction when associated with removal of iron.

Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Constituent Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significant, Texas Department of Health (1988) Drinking Water Standard Maximum Constituent Level (MCL) and Method of Removal
Radon (Rn)	Radon, a strongly radioactive, alpha-emitting noble gas, is a product of the disintegration of radium isotopes 223, 224, and 226. Radon-222 produced from the decay of radium-226 has a 3.8 day half-life and is the only radon isotope of importance in the water environment because the other radon isotopes have very short half-lives of less than a minute. Radon-222 decays through a series of other isotopes to lead-210. In water analyses, radon-222 concentrations are measured and reported in picocuries per liter (pCi/l). The detection of radon-222 is best obtained by immediate analysis, because of its short half-life, and its loss from solution to the atmosphere. Radon commonly occurs in ground waters in areas having significant concentrations of radium in igneous rocks, uranium ore bodies, clastic sedimentary rocks such as certain shales and sandstones, and volcanic tuffs. Investigations have found that ground waters of the Ogallala aquifer in part of the Texas High Plains had radon concentrations of about 100 to 1,000 pCi/l, that the ground waters of the Hickory aquifer around the Llano uplift of central Texas had radon concentrations of less than 100 pCi/l and up to 1,400 pCi/l, and that radon concentrations in the ground waters of the Gulf Coast aquifer in the Houston area ranged from undetectable amounts to as much as 3,300 pCi/l.	Radon-222 is not known to have any essential function for human metabolic needs. Excessive cumulative exposure to radon-222 and its daughter products has been associated strongly with lung cancer and probably emphysema. Radon-222 gas is emitted from parent rocks and ground water within such rocks. Water wells completed in aquifers having concentrations of uranium and radium are probably conveyors of radon gas to the land surface. Also water pumped by such wells can deliver radon gas to dwellings and other enclosed structures. Radon at elevated levels poses greater health risks than any other constituent currently regulated by the Safe Drinking Water Act. The MCL for radon has not yet been determined. Method of Removal: Aeration of water and ventilation to the atmosphere.
Selenium (Se)	Selenium is a rare non-metallic element which is widely distributed in sediments in very small amounts and is chemically similar to sulfur. In the presence of iron, selenium is co-precipitated with the mineral pyrite. One selenium mineral, ferroselite, may be associated with uranium ore deposits. Selenium is found in oxidizing solutions as the anions SeO_3 -2, and SeO_4 -2. These anions are unstable and are readily reduced to insoluble selenium SeO_2 and SeO_3 compounds. Industrial Uses and Sources: Manufacture and production of photoelectric cells, television cameras, copying machines, solar batteries and rectifiers, colored glass and ceramics, and hard rubber. Its aqueous mobility is limited by geochemical controls, and its concentration in natural waters rarely exceeds 0.001 mg/l. Concentrations of 1 to 3 mg/l have been detected in shallow ground waters effected by irrigation drainage waters.	Selenium is an essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is 0.015 mg/day which is 8 percent of the average daily intake of 0.19 mg/day from food, water and air. A deficiency may result in muscle diseases (myopathies) and possible liver damage. Adverse effects from excessive concentrations may include growth inhibition, liver damage, and an inflammation of the skin (dermatitis). Certain plants take-up and accumulate selenium from the soil and may have concentrations which may cause certain diseases in livestock and other grazing animals. Primary drinking water standard MCL is currently 0.01 mg/l and is to be increased to 0.05 mg/l. Method of Removal: Ion exchange, activated aluminum or reverse osmosis for SeO_4 -2, and ion exchange, reverse osmosis or distillation for SeO_3 -2.
Silica (SiO_2)	The non-metallic element silicon is second only to oxygen in abundance in crustal rocks. The chemical bond between silicon and oxygen is very strong and the silicon ion (Si +4) is the right size to fit closely in the center of four closely packed oxygen ions. This SiO_4 -4 tetrahedron is a building block of most minerals in igneous and metamorphic rocks. The term "silica", meaning the oxide SiO_2, is widely used in referring to silicon in natural water, but the actual form is $Si(OH)_4$ or H_4SiO_4, the hydrated ion. The main sources of silica are from silicate rocks which have quartz, chert, feldspars, ferro-magnesium and clay minerals. Silicates make-up about 95 percent of crustal rocks. Industrial Uses and Sources: Silicon is used in the manufacture and production of integrated circuits, transistors, solar cells and other electronic devices; silica is the main ingredient of glass; silicates and silicones are used as grinding and polishing material and in the manufacture and production of rubber, insulators, lubricants and water repellents. Concentrations of silica in natural waters range	The beneficial or hazardous significance of silica concentrations in waters used for drinking or irrigation purposes is unknown. Silica in the presence of calcium and magnesium, forms scale in pipes, boilers, and steam turbines that retard heat, and is difficult to remove. Silica inhibits deterioration of zeolite-type water softeners. Silica when added to soft water inhibits the corrosion of iron pipes. MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.

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Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Constituent Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significant, Texas Department of Health (1988) Drinking Water Standard Maximum Constituent Level (MCL) and Method of Removal
Silica **(SiO_2)** ***(continued)***	generally from 1 to 30 mg/l. Concentrations of silica up to 100 mg/l are common in some areas. The median concentration for silica in ground water is about 17 mg/l. Higher values are generally found in ground water and are related to rock type, water temperature and/or pollution.	
Silver **(Ag)**	Silver, a rare metallic element, is found mostly in igneous rocks and such sedimentary rocks as shales and carbonates. It can be found as native metallic silver or in such minerals as argneite, proustite, cerargyritye, and several other silver bearing minerals. Silver occurs in ground water as the cations Ag +2 and Ag +1. It may also occur in complex anionic form as $Ag[IO_4(OH)_2]$ -5. Industrial Uses and Sources: Manufacture and production of jewelry, coins, tableware, dental fillings and alloys, and is used mostly for the production of photographic film. As a consequence, it may be concentrated in surface waters and ground waters around industries producing or using photographic film. The average concentration in natural waters is about 0.0003 mg/l.	Silver is a non-essential element for human metabolic needs. Drinking water is believed to contribute about 7 percent of an adult human's average daily intake from food, water and air. Suggested intake should be none. An adverse effect from excessive concentrations of silver may be a permanent dark discoloration of the skin (argyria). Primary drinking water standard MCL is 0.05 mg/l. Method of Removal: Ion exchange, reverse osmosis or distillation.
Sodium **(Na)** **and** **Potassium** **(K)**	Sodium, an abundant alkaline-earth metallic element, is dissolved from such minerals and rocks as feldspars, clay minerals, halite, and other evaporites. Sodium is the sixth most abundant element in crustal rocks. The ionic forms of sodium in water are the predominant cation Na +1 and such complex ions as $NaCO_3$ -1, $NaHCO_3$ (aqueous) and $NaSO_4$ -1. Industrial Uses and Sources: Production of table salt, and many uses in industry, medicine, agriculture and photography. Potassium is a less abundant alkaline-earth metallic element which makes-up about 2.5 percent of crustal rocks and is dissolved from such minerals as carnallite, sylvite, feldspars, mica and clay minerals. The ionic form of potassium in ground water is the cation K +1. The isotope potassium-40 is radioactive. Industrial Uses and Sources: Manufacture and production of alloys for certain nuclear reactors; while potassium compounds are used in making glass, soap, matches, explosives, medicines, and fertilizers. Sodium concentrations are probably less than 60 mg/l in most fresh natural waters, and as high as 1,000 mg/l in some western streams, about 10,000 mg/l in sea water, and 25,000 mg/l in brines. Relatively high concentrations of sodium are found in most industrial waste effluent waters. Potassium concentrations in natural waters are generally less than 10 mg/l, as much as 100 mg/l in hot springs, and as much as 25,000 mg/l in brines.	Sodium and potassium are essential elements for human metabolic needs. The suggested average daily intake by an adult human for sodium is 2,200 mg/day from food, water, and air. The actual average daily intake is 5,656 mg/day with less than one (1) percent contributed by drinking waters. A deficiency of sodium may result in a deficiency in the blood (hyponatremia) and muscle fatigue. Excessive sodium is believed to cause high blood pressure; consequently, a maximum level concentration of 20 mg/l in drinking water is recommended for most persons having high blood pressure. Sodium in combination with chloride, gives a salty taste to water. A high sodium content may limit the use of water for irrigation (see percent sodium, SAR, and RSC). The suggested average daily intake by adult humans for potassium is 3,754 mg/day from food, water and air with less than one (1) percent (38 mg/day) contributed by drinking waters. A deficiency of potassium may result in a deficiency in the blood (hypokalemia) and muscle weakness. The toxicity from excessive potassium may include diarrhea, excess amount in the blood (hyperkalemia) and poisoning of the kidney (nephrotoxicity). Plants require a certain amount of potassium for healthy growth. More than 50 mg/l of sodium and potassium in the presence of suspended matter can cause foaming in steam boilers. MCL for sodium and MCL for potassium have not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.
Strontium **(Sr)**	Stable (non-radioactive) strontium is a moderately abundant alkaline-earth metallic element which is similar to calcium but much less soluble. Strontium is dissolved from such minerals as strontianite and celestite which are found mostly in igneous rocks and such sedimentary rocks as shales and carbonates. The ionic form of strontium found in water is the cation Sr +1. Strontium-90 is a radioactive isotope found in fall out from certain nuclear explosions. Industrial Uses and Sources: Manufacture and production of flares, fireworks, medicines, batteries, paints, rubber, glass and is used in the recovery of sugar from sugar beets and molasses. The median content of	The beneficial or hazardous significance of strontium concentrations in waters used for drinking, industrial or irrigation purposes is unknown. Strontium is known to contribute to the hardness of water (see hardness as $CaCO_3$). MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.

(continued next page)

Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Constituent Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significant, Texas Department of Health (1988) Drinking Water Standard Maximum Constituent Level (MCL) and Method of Removal
Strontium **(Sr)** ***(continued)***	strontium in most natural waters used for public supplies is about 0.11 mg/l. High strontium concentrations greater than 1 mg/l have been detected in ground waters in Wisconsin, Ohio, Florida, and Texas where celestite and/or strontianite are common minerals in carbonate rocks. The strontium concentration can be very high in some brines.	
Sulfate **(SO_4)**	The chief sources of sulfur, a moderately abundant non-metallic element, are evaporitic sedimentary rocks. In water sulfur occurs in the oxidation state as the sulfate anion SO_4-1. Industrial Uses and Sources: Production of sulfuric acid and sulfur compounds for manufacturing and production of various chemicals, metals, paper pulp, textiles, fertilizers, explosives, fungicides, insecticides, rubber, shampoos, batteries, photographic film, and medicines. Sulfate is present in sewage and found in large amounts in oil-field brines, sea water, and various industrial wastewaters. Natural waters commonly have concentrations less than 1,000 mg/l. Most fresh drinking waters have less than 300 mg/l of sulfate. Low sulfate concentrations can result from bacterial reduction of sulfate in anaerobic sediments of certain aquifers. Magnesium and sodium sulfates are highly soluble minerals, and water containing these compounds can attain sulfate concentrations in excess of 100,000 mg/l.	Sulfate is a non-essential constituent for human metabolic needs. The average daily intake of sulfur by an adult human from drinking water is about 9.2 mg/day. Any high concentration in drinking water is undesirable. Water containing about 500 mg/l sulfate tastes bitter. Excessively high concentrations of sulfate in water causes inflammation of the stomach and intestines (gastroenteritis), producing such symptoms as diarrhea, abdominal cramps, nausea, vomiting, and fever, especially in infants and children. Secondary drinking water standard MCL is 300 mg/l. Method of Removal: Distillation, reverse osmosis or ion exchange.
Thorium **(Th)**	Thorium, a radioactive actinide metallic element, may be more abundant than uranium in most types of rocks. It occurs in such minerals as monarite, thorite, thorianite, and thorbastraesite which are found in such igneous rocks as granites and syenites. Industrial Uses and Sources: Production of uranium-233 for nuclear fuels and manufacture of strong alloys and photoelectric cells. Thorium-232 decay products include isotopes of radium, radon and lead (see radium, radon and lead). The water geochemistry of thorium is not well known. In water, thorium occurs only as the tetravalent cation Th +4, and the low solubility of the oxide tends to keep thorium in its parent minerals. Not much is known about the concentration of thorium in natural waters due to lack of analyses. Expected range of concentrations in fresh water is probably about 0.00001 to 0.001 mg/l.	Thorium is not known to be an essential element for human metabolic needs. The known impact of thorium in water quality is related to the toxicity from its radioactive disintegration products such as radium-228 (see radium) and its beta particle emissions (see gross beta). MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.
Titanium **(Ti)**	Titanium, a transition metallic element, is one of the most abundant elements in crustal rocks. It is particularly abundant in igneous rocks, and because it is resistant to weathering, it is also abundant and in some clastic sedimentary rocks such as sandstones and shales. It is present in such minerals as rutile, anatase, ilmenite and certain other iron-bearing minerals. Industrial Uses and Sources: Manufacture and production of paint pigment, dyes, ceramics, electrical components, leather dyes, textiles and alloys. It is well known for its resistance to corrosion. Titanium is very insoluble in water, consequently concentrations in natural waters are very low. Only the cation Ti +4 should be expected in nautral waters. Analyses of titanium in some natural waters for public supply had concentrations of less than 0.0015 mg/l. Analyses of acidic (low pH) waters and some brines have detected concentrations of more than 1.0 mg/l.	The beneficial or hazardous significance of titanium concentrations in waters used for drinking, industrial or irrigation purposes is unknown. MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.

Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Constituent Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significant, Texas Department of Health (1988) Drinking Water Standard Maximum Constituent Level (MCL) and Method of Removal
Uranium (U)	Uranium, a moderately abundant radioactive actinide metallic element with relatively weak radioactivity, occurs in various igneous, metamorphic and sedimentary rocks. The uranium nuclide is the starting point in a radioactive decay series that ends with the stable isotope, lead-206. The primary uranium-bearing minerals are uraninite, pitchblende, carontite and uranyl nityrate. The ionic forms of uranium found in ground water are the cations UO_2 +1, U +2, and U +4 and the anions $UO_2(CO)_2$-2, $UO_2(OH)_3$-1 and other complex anionic forms. Industrial Uses and Sources: Used for nuclear power, nuclear weapons, and paint manufacturing; also, uranium is used in medical research as a radiation source, in scientific research to produce various isotopes and for the production of the artificial elements neptunium and plutonium. Most natural waters have concentrations ranging between 0.0001 and 0.01 mg/l. Concentrations of 1.0 mg/l to about 15 mg/l have been detected in natural waters in and near uranium-bearing rocks and ore bodies.	Uranium is not known to be an essential element for human metabolic needs. It can cause various cancers, and is a bone seeking radioactive element much like radium. The critical organ for its toxicity is the kidney. The known impact of uranium in water quality is related to the toxicity from its radioactive disintegration products such as radium-226 (see radium) and its alpha particle emissions (see gross alpha). MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.
Vanadian (V)	Vanadium, a relatively rare transition metallic element, is found in the minerals patronite, vanadinite and carrotite which occur in certain lead and uranium ore deposits. The dominant ionic forms of vanadium in ground water are V +5 anionic complexes with oxide and hydroxide. Industrial Uses and Sources: Manufacture and production of special steels for locomotive, automobile, and truck cylinders, pistons and bushings, and for high speed tools and die blocks; and also used as a catalyst. Alloys of vanadium are very rust and corrosion resistant. Its aqueous geochemistry is rather complicated, and fairly high solubility can be expected in oxidizing alkaline environments around ore bodies. However, natural waters rarely have concentrations greater than 0.01 mg/l. Concentration of a few tenths of a mg/l have been detected in acidic (low pH) waters from thermal springs.	Vanadium may or may not be an essential element for human metabolic needs. The effect of a deficiency is unknown. Adverse effects from excessive concentrations may include inflammation of the stomach and intestines (gastroenteritis), producing diarrhea, abdominal cramps, nausea, vomiting and fever. MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.
Zinc (Zn)	Zinc is a moderately abundant metallic element in crustal rocks, occurring in such minerals as sphalerite, zincite, franklinite, smithsonite, willemite and hemimorphite. The ionic form of zinc in ground water is the cation Zn +2. Industrial Uses and Sources: Used widely in galvanizing, electroplating and metallurgy, and in the manufacturte and production of paints, rubber, cosmetics, plastics, soap, paper, and synthetic fibers. Natural waters have a median concentration of 0.02 mg/l. Waters effected by mine drainage commonly contain 0.1 mg/l or more of zinc.	Zinc is an essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is 0.39 mg/day which is 3 percent of the average daily intake of 13 mg/day from food, water, and air. A deficiency may result in reduced appetite and growth. Adverse effects from excessive concentrations may include irritability, muscle stiffness and pain, loss of appetite, and nausea. Secondary drinking water standard MCL is 5.0 mg/l. Method of Removal: Reverse osmosis, distillation, or ion exchange.
Dissolved Solids	Dissolved solids (DS) are the approximate total amount of mineral constituents dissolved in water. The measured DS concentration is used in Texas to classify waters according to various degrees of salinity. Waters containing 1,000 mg/l or less DS are considered fresh; those containing 1,001 to 3,000 mg/l DS are slightly saline; those containing 3,001 to 10,000 mg/l DS are moderately saline; those containing 10,001 to 35,000 mg/l DS are very saline; and those with more than 35,000 mg/l DS are brines. Usable waters commonly contain 3,000 mg/l DS or less. Some brines contain as much as 300,000 mg/l DS.	The Texas Department of Health (1988) secondary drinking water standard MCL is 1,000 mg/l for dissolved solids. It is recommended that waters having dissolved solids concentrations exceeding this MCL not be used for drinking purposes, if other less mineralized water supplies are available. For many purposes, the dissolved-solids concentration is a major limitation on water use. Method of Removal: Distillation, ion exchange or reverse osmosis.

Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Constituent Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	**Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters**	**Significant, Texas Department of Health (1988) Drinking Water Standard Maximum Constituent Level (MCL) and Method of Removal**
Hardness as ($CaCO_3$)	Hardness of water is caused principally by calcium and magnesium ions, but barium and strontium, free acid ions, and heavy-metal ions contribute to hardness also. Hardness as $CaCO_3$ is equal to Ca +Mg+Ba+Sr(me/l)x50.05. If Ba and Sr are not measured, the hardness as [$CaCO_3$ (mg/l) x 2.5] + [Mg (mg/l) x 4.1]. Non carbonate hardness (mg/l) equivalent $CaCO_3$ is equal to (me/l hardness - me/l alkalinity) x 50.05. Water with hardness as $CaCO_3$ of 0 to 60 mg/l is considered soft, of 61 to 120 mg/l is considered moderately hard, of 121 to 180 mg/l is considered hard, and of more than 180 mg/l is considered very hard. Most ground waters in Texas are hard to very hard.	Water low in hardness causes corrosion of metallic surfaces. Hard water consumes excessive amounts of soap, and causes the deposit of soap curd on bathtubs. Hard water forms scale in boilers, water heaters, hot water using appliances and pipes. Hardness equivalent to CO_3 and HCO_3 is called carbonate hardness. Any hardness in excess of this is called non-carbonate hardness. A carbonate hardness value of less than 100 mg/l is considered desirable for domestic use. MCL has not been determined. Method of Removal: Distillation, reverse osmosis and ion exchange.
Conductivity or Specific Conductance (micromhos per centimeter at 25°C)	Conductivity is an indicator of the salinity or mineral content of water, and can be used to estimate the dissolved-solids concentration. The approximate dissolved solids of most waters in mg/l is usually about 65 percent of the measured concudtivity of the water. Much higher percentages usually are associated with waters high in sulfate.	Conductivity is a measure of the electrical conductivity of water and varies with the amount of dissolved solids in the water. MCL has not been determined. The conductivity of water is used to determine the salinity hazard of irrigation waters. A conductivity of 2,250 micromhos/cm probably represents the upper limit of salinity that should be considered as being safe for use of the water for supplemental irrigation.
Hydrogen Ion Concentration (pH)	Acids, acid-generating salts, and free carbon dioxide in waters lower the pH. Carbonates, bicarbonates, hydroxides, phosphates, silicates, and borates raise the pH. The pH of most ground water ranges from 6.0 to 9.0.	A pH of 7.0 indicates the neutrality of a solution. Values of pH higher than 7.0 denote increasing alkalinity, while values of pH lower than 7.0 indicate increasing acidity. The pH is a measure of the activity of the hydrogen ions in solution. It may be expressed using hydrogen ion (H +1) concentration rather than the activity. The corrosiveness of water generally increases with decreasing pH. However, excessively alkaline waters with very high pH may also attack metals. Secondary drinking water standard is 7.0 or greater.
Percent Sodium (% Na)	As an indicator of the sodium hazard of irrigation waters. Calculated as follows by using me/l: $\%Na = Na(100)\,(Na+K+Mg+Ca)$	Percent sodium is the ratio of the sodium ions to total cations times 100. A sodium percentage exceeding 60 percent is a warning of a sodium hazard. Continued irrigation with this type of water will impair the tilth and permeability of the soil.
Sodium Adsorption Ratio (SAR)	An indicator of the sodium hazard of irrigation waters. Calculated as follows using me/l: $SAR = Na/\sqrt{(Ca + Mg/2}$	The SAR is the ratio for soil extracts and irrigation waters used to express the relative activity of sodium ions in exchange reactions with the soil. An SAR of 14 is probably the upper limit for waters that can be safely used for supplemental irrigation.
Residual Sodium Carbonate (RSC)	An indicator of the sodium hazard of irrigation waters. Calculated as follows using me/l: $RSC = (CO_3+HCO_3) - (Ca+Mg)$ or RSC = 0.02 (Total Alkalinity - Hardness)	As calcium and magnesium precipitates as carbonates in the soil, the relative proportion of sodium in the water is increased. Waters having 1.25 to 2.50 me/l of RSC are probably marginal for irrigation use, and those having greater than 2.50 me/l RSC probably are not suited for irrigation.

Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Constituent Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significant, Texas Department of Health (1988) Drinking Water Standard Maximum Constituent Level (MCL) and Method of Removal

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***Note:** This table was reviewed by personnel of the Division of Water Hygiene of the Texas Department of Health (June 1989).*

APPENDIX B
Water Quality Summaries for the Paleozoic and Cretaceous Aquifers

The following tables provide water-quality summaries for the named aquifers.

Aquifer: Hickory

Constituent	MCL (mg/l)	Number of Analyses Made	Constituent Concentrations in Study Area		Approximate Percent Distribution	
			Range (mg/l)	Average (mg/l)	Exceed Average	Exceed MCL
Nitrate	44.3	35	<0.4 to 111	7.6	20	3
Fluoride	4.0	37	0.2 to 2.4	0.8	22	0
Fluoride	2.0	37	0.2 to 2.4	0.8	22	3
Chloride	300	48	10 to 653	83	31	4
Sulfate	300	48	7 to 267	55	31	0
Dissolved Solids	1,000	45	320 to 1,610	554	36	8
Sodium	20	42	7 to 240	60	38	62
Hardness as $CaCO_3$	None	41	120 to 690	369	51	—

Aquifer: Mid-Cambrian

Constituent	MCL (mg/l)	Number of Analyses Made	Constituent Concentrations in Study Area		Approximate Percent Distribution	
			Range (mg/l)	Average (mg/l)	Exceed Average	Exceed MCL
Nitrate	43.3	31	<0.4 to 265	23.9	26	10
Fluoride	4.0	10	0.4 to 4.0	1.4	20	0
Fluoride	2.0	10	0.4 to 4.0	1.4	20	20
Chloride	300	33	7 to 378	50	27	3
Sulfate	300	33	7 to 103	30	24	0
Dissolved Solids	1,000	32	240 to 966	491	41	0
Sodium	20	28	1 to 320	46	29	46
Hardness as $CaCO_3$	None	29	108 to 634	369	55	—

Aquifer: Ellenburger-San Saba

Constituent	MCL (mg/l)	Number of Analyses Made	Constituent Concentrations in Study Area		Approximate Percent Distribution	
			Range (mg/l)	Average (mg/l)	Exceed Average	Exceed MCL
Nitrate	43.3	37	<0.4 to 56	11.8	32	5
Fluoride	4.0	38	0.1 to 1.7	0.5	45	0
Fluoride	2.0	38	0.1 to 1.7	0.5	45	0
Chloride	300	50	9 to 122	38	34	0
Sulfate	300	50	8 to 91	35	42	0
Dissolved Solids	1,000	38	317 to 718	452	47	0
Sodium	20	37	6 to 61	24	41	51
Hardness as $CaCO_3$	None	50	260 to 626	384	40	—

Aquifer: Marble Falls

Constituent	MCL (mg/l)	Number of Analyses Made	Constituent Concentrations in Study Area Range (mg/l)	Average (mg/l)	Approximate Percent Distribution Exceed Average	Exceed MCL
Nitrate	44.3	11	1.8 to 705	131	18	27
Fluoride	4.0	4	0.1 to 0.4	0.2	25	0
Fluoride	2.0	4	0.1 to 0.4	0.2	25	0
Chloride	300	16	15 to 167	53	25	0
Sulfate	300	15	11 to 136	30	27	0
Dissolved Solids	1,000	12	339 to 1,560	580	17	17
Sodium	20	10	2 to 80	21	40	50
Hardness as $CaCO_3$	None	15	252 to 1,120	459	27	-

Aquifer: Lower Trinity

Constituent	MCL (mg/l)	Number of Analyses Made	Constituent Concentrations in Study Area Range (mg/l)	Average (mg/l)	Approximate Percent Distribution Exceed Average	Exceed MCL
Nitrate	44.3	88	<0.4 to 69	4.3	24	2
Fluoride	4.0	95	0.0 to 5.3	1.8	39	8
Fluoride	2.0	95	0.0 to 5.3	1.8	39	34
Chloride	300	94	11 to 2,440	173	18	13
Sulfate	300	94	15 to 1,790	265	33	31
Dissolved Solids	1,000	95	239 to 4,663	969	35	35
Sodium	20	91	6 to 1,500	183	35	80
Hardness as $CaCO_3$	None	87	61 to 1,920	373	34	-

Aquifer: Middle Trinity

Constituent	MCL (mg/l)	Number of Analyses Made	Constituent Concentrations in Study Area Range (mg/l)	Average (mg/l)	Approximate Percent Distribution Exceed Average	Exceed MCL
Nitrate	44.3	249	<0.4 to 155	6.3	17	3
Fluoride	4.0	264	0.0 to 7.0	B-3 1.5	39	7
Fluoride	2.0	264	0.0 to 7.0	1.5	39	25
Chloride	300	277	4 to 620	46	23	2
Sulfate	300	281	2 to 3,360	252	22	20
Dissolved Solids	1,000	266	179 to 5,690	704	28	15
Sodium	20	271	2 to 1,020	49	27	52
Hardness as $CaCO_3$	None	284	91 to 3,060	545	24	—

Aquifer: **Upper Trinity**

Constituent	MCL (mg/l)	Number of Analyses Made	Constituent Concentrations in Study Area		Approximate Percent Distribution	
			Range (mg/l)	Average (mg/l)	Exceed Average	Exceed MCL
Nitrate	44.3	135	<0.4 to 88	5.1	24	2
Fluoride	4.0	128	0.0 to 5.5	1.4	35	6
Fluoride	2.0	128	0.0 to 5.5	1.4	35	28
Chloride	300	148	2 to 640	27	18	<1
Sulfate	300	149	4 to 2,370	360	26	26
Dissolved Solids	1,000	139	227 to 4,758	860	25	20
Sodium	20	140	4 to 1,050	26	20	24
Hardness as $CaCO_3$	None	145	206 to 2,460	680	27	—

Aquifer: **Edwards Plateau**

Constituent	MCL (mg/l)	Number of Analyses Made	Constituent Concentrations in Study Area		Approximate Percent Distribution	
			Range (mg/l)	Average (mg/l)	Exceed Average	Exceed MCL
Nitrate	43.3	105	<04 to 384	19.0	23	10
Fluoride	4.0	100	0.0 to 0.8	0.3	22	0
Fluoride	2.0	100	0.0 to 0.8	0.3	22	0
Chloride	300	108	2 to 256	33	32	0
Sulfate	300	106	<4 to 130	14	30	0
Dissolved Solids	1,000	105	105 to 1,310	357	34	1
Sodium	20	105	<1 to 150	20	32	32
Hardness as $CaCO_3$	None	108	101 to 539	295	49	—

APPENDIX C

Distribution of Nitrate, Fluoride and Sulfate Concentrations by Range in Concentration Categories, Averages and Medians for the Paleozoic and Cretaceous Aquifers

APPENDIX C-1

Distribution of Nitrate Concentrations by Range in Concentration Categories, Averages and Medians for the Paleozoic and Cretaceous Aquifers

The following table provides the distribution of nitrate concentrations by range in concentration Categories, averages, and medians, for the Hickory aquifer.

		Distribution By Ranges in Concentration Categories in Milligrams Per Liter (mg/l)					Average and Median Concentrations		
County(s) and Other	Number of Analyses	<0.4 to 1.0	1.1 to 5.0	5.1 to 10.6	10.7 to 44	>44.3	Arithmetic Averages (mg/l)	Analyses Medians (mg/l)	Category Median (mg/l)
Blanco and Gillespie	35	19	9	2	4	1	7.6	56	—
Percent Distribution	100	54.3	25.7	5.7	11.4	2.9	—	—	—
By Categories									
Range in Analyses	—	<0.4-0.8	1.1-3.5	9.0-9.4	15-43	111	—	—	—
Arithmetic Averages	—	0.3±	2.2	9.2	28	111	7.6		
Analyses Medians	—	0.40±	2.30	9.20	29.00	111	—	7.8	—
Category Medians	—	0.50	3.05	7.85	27.35	111	—	—	7.8

Notes: 2.9% Exceed Primary Standard MCL of 44.3 mg/l.
14.3% Exceed Regional Average of 10.6 mg/l.
45.7% Exceed Ambient Level of 1.0 mg/l or less.

The following table provides the distribution of nitrate concentrations by range in concentration Categories, averages, and medians, for the Mid-Cambrian aquifer.

		Distribution By Ranges in Concentration Categories in Milligrams Per Liter (mg/l)					Average and Median Concentrations		
County(s) and Other	Number of Analyses	<0.4 to 1.0	1.1 to 5.0	5.1 to 10.6	10.7 to 44	>44.3	Arithmetic Averages (mg/l)	Analyses Medians (mg/l)	Category Median (mg/l)
Blanco and Gillespie	31	7	5	6	10	3	23.9	133	—
Percent Distribution	100	22.6	16.1	19.4	32.2	9.7	—	—	—
By Categories									
Range in Analyses	—	<0.4-1.0	1.1-5.0	6.0-10.0	15-41	58-265	—	—	—
Arithmetic Averages	—	0.2±	2.9	7.3	25	144	23.9		
Analyses Medians	—	0.50±	3.05	8.00	28.00	162	—	26.9	—
Category Medians	—	0.50	3.05	7.85	27.35	162	—	—	26.6

Notes: 9.7% Exceed Primary Standard MCL of 44.3 mg/l.
41.9% Exceed Regional Average of 10.6 mg/l.
77.4% Exceed Ambient Level of 1.0 mg/l or less.

The following table provides the distribution of nitrate concentrations by range in concentration Categories, averages, and medians, for the Ellenburger-San Saba aquifer.

		Distribution By Ranges in Concentration Categories in Milligrams Per Liter (mg/l)					Average and Median Concentrations		
County(s) and Other	Number of Analyses	<0.4 to 1.0	1.1 to 5.0	5.1 to 10.6	10.7 to 44	>44.3	Arithmetic Averages (mg/l)	Analyses Medians (mg/l)	Category Median (mg/l)
Blanco and Gillespie	37	8	6	9	12	2	11.8	28.1	—
Percent Distribution	100	21.6	16.2	24.3	32.5	5.4	—	—	—
By Categories									
Range in Analyses	—	0.1-0.8	1.1-4.8	6.0-9.7	10.7-34	54-46	—	—	—
Arithmetic Averages	—	0.3	2.7	7.7	20	55	11.8		
Analyses Medians	—	0.45	2.95	7.85	22.35	55	—	12.7	—
Category Medians	—	0.50	3.05	7.85	27.35	55	—	—	14.3

Notes: 5.4% Exceed Primary Standard MCL of 44.3 mg/l.
37.8% Exceed Regional Average of 10.6 mg/l.
78.4% Exceed Ambient Level of 1.0 mg/l or less.

The following table provides the distribution of nitrate concentrations by range in concentration Categories, averages, and medians, for the Marble Falls aquifer.

		Distribution By Ranges in Concentration Categories in Milligrams Per Liter (mg/l)					Average and Median Concentrations		
County(s) and Other	Number of Analyses	<0.4 to 1.0	1.1 to 5.0	5.1 to 10.6	10.7 to 44	>44.3	Arithmetic Averages (mg/l)	Analyses Medians (mg/l)	Category Median (mg/l)
Blanco	11	0	1	0	7	3	131	353	—
Percent Distribution	100	0	9.1	0	63.6	27.3	—	—	—
By Categories									
Range in Analyses	—	0	1.8	0	11-38	70-705	—	—	—
Arithmetic Averages	—	0	1.8	0	27	418	131		
Analyses Medians	—	-	1.8	0	24.50	388	—	122	—
Category Medians	—	0	3.05	0	27.35	388	—	—	124

Notes: 27.3% Exceed Primary Standard MCL of 44.3 mg/l.
90.9% Exceed Regional Average of 10.6 mg/l.
100% Exceed Ambient Level of 1.0 mg/l or less.

The following table provides the distribution of nitrate concentrations by range in concentration Categories, averages, and medians, for the Lower Trinity aquifer.

		Distribution By Ranges in Concentration Categories in Milligrams Per Liter (mg/l)					Average and Median Concentrations		
County(s) and Other	Number of Analyses	<0.4 to 1.0	1.1 to 5.0	5.1 to 10.6	10.7 to 44	>44.3	Arithmetic Averages (mg/l)	Analyses Medians (mg/l)	Category Median (mg/l)
Bandera	5	5	0	0	0	0	0.5	0.5	—
Hays	8	4	3	1	0	0	2.7	3.0	—
Kendall	6	4	1	0	1	0	5.1	14.0	—
Kerr	3	3	0	0	0	0	<0.4	<0.4	—
Travis	66	42	10	7	5	2	4.9	34.6	—
Totals	**88**	**58**	**14**	**8**	**6**	**2**	**4.3**	**34.6**	—
Percent Distribution	100	65.9	15.9	9.1	6.8	2.3	—	—	—
By Categories									
Range in Analyses	—	<0.4-1.0	1.1-5.0	5.9-10.0	17-44	56-69	—	—	—
Arithmetic Averages	—	0.1±	3.3	6.9	24	63	4.3	—	—
Analyses Medians	—	0.50±	3.25	7.95	30.50	62.50	—	4.9	—
Category Medians	—	0.50	3.05	7.85	27.35	62.50	—	—	4.6

Notes: 2.3% Exceed Primary Standard MCL of 44.3 mg/l.
9.1% Exceed Regional Average of 10.6 mg/l.
34.1% Exceed Ambient Level of 1.0 mg/l or less.

The following table provides the distribution of nitrate concentrations by range in concentration Categories, averages, and medians, for the Middle Trinity aquifer.

		Distribution By Ranges in Concentration Categories in Milligrams Per Liter (mg/l)					Average and Median Concentrations		
County(s) and Other	Number of Analyses	<0.4 to 1.0	1.1 to 5.0	5.1 to 10.6	10.7 to 44	>44.3	Arithmetic Averages (mg/l)	Analyses Medians (mg/l)	Category Median (mg/l)
Bandera	15	13	2	0	0	0	0.6	2.4	—
Blanco	20	9	2	3	4	2	13.3	32.1	—
Comal	8	3	4	1	0	0	2.5	3.1	—
Hays	36	25	9	2	0	0	1.0	3.6	—
Gillespie	22	5	4	4	6	3	23.2	78	—
Kendall	65	36	14	7	7	1	6.5	74	—
Kerr	21	20	0	0	1	0	2.0	19.1	—
Travis	62	32	17	7	5	1	2.4	32.1	—
Totals	**249**	**143**	**52**	**24**	**23**	**7**	**6.3**	**78**	—
Percent Distribution	100	57.4	20.9	9.6	9.3	2.8	—	—	—
By Categories									
Range in Analyses	—	<0.4-1.0	1.1-5.0	5.1-10.0	14-44	49-155	—	—	—
Arithmetic Averages	—	0.1±	2.7	7.2	27	89	6.3	—	—
Analyses Medians	—	0.50±	3.05	7.75	29.00	102	—	7.2	—
Category Medians	—	0.50	3.05	7.85	27.35	102	—	—	7.1

Notes: 2.8% Exceed Primary Standard MCL of 44.3 mg/l.
12.1% Exceed Regional Average of 10.6 mg/l.
42.6% Exceed Ambient Level of 1.0 mg/l or less.

The following table provides the distribution of nitrate concentrations by range in concentration Categories, averages, and medians, for the Upper Trinity aquifer.

		Distribution By Ranges in Concentration Categories in Milligrams Per Liter (mg/l)					Average and Median Concentrations		
County(s) and Other	Number of Analyses	<0.4 to 1.0	1.1 to 5.0	5.1 to 10.6	10.7 to 44	>44.3	Arithmetic Averages (mg/l)	Analyses Medians (mg/l)	Category Median (mg/l)
Bandera	24	15	4	3	2	0	2.7	8.0	—
Blanco	12	2	6	3	1	0	7.2	20.6	—
Hays	26	10	7	6	1	2	7.4	30.0	—
Kendall	12	6	2	2	2	0	5.7	16.5	—
Kerr	5	2	3	0	0	0	1.1	1.2	—
Medina	8	0	5	3	0	0	4.3	5.0	—
Travis	48	28	12	3	4	1	4.9	44.1	—
Totals	135	63	39	20	10	3	5.1	44.1	—
Percent Distribution	100	46.7	28.9	14.8	7.4	2.2	—	—	—
By Categories									
Range in Analyses	—	<0.4-1.0	1.1-5.0	5.1-10.2	11-43	55-88	—	—	—
Arithmetic Averages	—	0.1±	2.6	7.1	24	68	5.1	—	—
Analyses Medians	—	0.50±	3.05	7.65	27.00	72	—	5.8	—
Category Medians	—	0.50	3.05	7.85	27.35	72	—	—	5.9

Notes: 2.2% Exceed Primary Standard MCL of 44.3 mg/l.
9.6% Exceed Regional Average of 10.6 mg/l.
53.3% Exceed Ambient Level of 1.0 mg/l or less.

The following table provides the distribution of nitrate concentrations by range in concentration Categories, averages, and medians, for the Edwards Plateau aquifer.

		Distribution By Ranges in Concentration Categories in Milligrams Per Liter (mg/l)					Average and Median Concentrations		
County(s) and Other	**Number of Analyses**	**<0.4 to 1.0**	**1.1 to 5.0**	**5.1 to 10.6**	**10.7 to 44**	**>44.3**	**Arithmetic Averages (mg/l)**	**Analyses Medians (mg/l)**	**Category Median (mg/l)**
Bandera	17	1	5	5	4	2	16.9	5.3	—
Gillespie	85	26	22	10	19	8	19.9	19.2	—
Kerr	3	1	2	0	0	0	2.3	2.8	—
Totals	**105**	**28**	**29**	**15**	**23**	**10**	**19.0**	**192**	**—**
Percent Distribution	100	26.7	27.6	14.3	21.9	9.5	—	—	—
By Categories									
Range in Analyses	—	<0.4-0.8	1.5-5.0	5.4-10.0	11-38	48-384	—	—	—
Arithmetic Averages	—	0.2±	3.2	6.8	22	129	19.0	—	—
Analyses Medians	—	0.40±	3.25	7.70	24.50	216	—	28.0	—
Category Medians	—	0.5	3.05	7.85	27.35	216	—	—	28.7

Notes: 9.5% Exceed Primary Standard MCL of 44.3 mg/l.
31.4% Exceed Regional Average of 10.6 mg/l.
73.3% Exceed Ambient Level of 1.0 mg/l or less.

APPENDIX C-2

Distribution of Fluoride Concentrations by Range in Concentration Categories, Averages and Medians for the Paleozoic and Cretaceous Aquifers

The following table provides the distribution of fluoride concentrations by range in concentration Categories, averages, and medians, for the Hickory aquifer.

		Distribution By Ranges in Concentration Categories in Milligrams Per Liter (mg/l)					Average and Median Concentrations		
County(s) and Other	Number of Analyses	0.0 to 0.5	0.6 to 1.2	1.3 to 2.0	2.1 to 4.0	>4.0	Arithmetic Averages (mg/l)	Analyses Medians (mg/l)	Category Median (mg/l)
Blanco and Gillespie	37	18	13	5	1	0	0.8	1.3	—
Percent Distribution	100	48.7	35.1	13.5	2.7	0	—	—	—
By Categories									
Range in Analyses	—	0.2-0.5	0.6-1.0	1.7-1.9	2.4	0	—	—	—
Arithmetic Averages	—	0.4	0.8	1.8	2.4	0	0.8	—	—
Analyses Medians	—	0.35	0.80	1.80	2.4	0	—	0.8	—
Category Medians	—	0.25	0.90	1.65	3.05	0	—	—	0.7

Notes: 2.7% Exceed Secondary Standard MCL of 2.0 mg/l.
None Exceed Primary Standard MCL of 4.0 mg/l.
16.2% Exceed Regional Average of 1.2 mg/l.

The following table provides the distribution of fluoride concentrations by range in concentration Categories, averages, and medians, for the Mid-Cambrian aquifer.

		Distribution By Ranges in Concentration Categories in Milligrams Per Liter (mg/l)					Average and Median Concentrations		
County(s) and Other	**Number of Analyses**	0.0 to 0.5	0.6 to 1.2	1.3 to 2.0	2.1 to 4.0	>4.0	**Arithmetic Averages (mg/l)**	**Analyses Medians (mg/l)**	**Category Median (mg/l)**
Blanco and Gillespie	10	3	4	1	2	0	1.4	2.2	—
Percent Distribution By Category	100	30.0	40.0	10.0	20.0	0	—	—	—
Range in Analyses	—	0.4-0.5	0.7-1.1	1.3	3.1-4.0	0	—	—	—
Arithmetic Averages	—	0.5	1.0	1.3	3.6	0	1.4	—	—
Analyses Medians	—	0.45	0.90	1.30	3.55	0	—	1.3	—
Category Medians	—	0.25	0.90	1.65	3.05	0	—	—	1.2

Notes: 30.0% Exceed Regional Average of 1.2 mg/l.
20.0% Exceed Secondary Standard MCL of 2.0 mg/l.
None Exceed Primary Standard MCL of 4.0 mg/l.

The following table provides the distribution of fluoride concentrations by range in concentration Categories, averages, and medians, for the Ellenburger-San Saba aquifer.

		Distribution By Ranges in Concentration Categories in Milligrams Per Liter (mg/l)					Average and Median Concentrations		
County(s) and Other	Number of Analyses	0.0 to 0.5	0.6 to 1.2	1.3 to 2.0	2.1 to 4.0	>4.0	Arithmetic Averages (mg/l)	Analyses Medians (mg/l)	Category Median (mg/l)
Blanco and Gillespie	38	21	16	1	0	0	0.5	0.9	—
Percent Distribution	100	55.3	42.1	2.6	0	0	—	—	—
By Category									
Range in Analyses	—	0.1-0.5	0.6-1.2	1.7	0	0	—	—	—
Arithmjetic Averages	—	0.3	0.7	1.7	0	0	0.5	—	—
Analyses Medians	—	0.30	0.90	1.7	0	0	—	0.6	—
Category Medians	—	0.25	0.90	1.65	0	0	—	—	0.6

Notes: None Exceed Secondary Standard MCL of 2.0 mg/l and Primary Standard MCL of 4.0 mg/l.
2.6% Exceed Regional Average of 1.2 mg/l.

The following table provides the distribution of fluoride concentrations by range in concentration Categories, averages, and medians, for the Marble Falls aquifer.

		Distribution By Ranges in Concentration Categories in Milligrams Per Liter (mg/l)					Average and Median Concentrations		
County(s) and Other	**Number of Analyses**	0.0 to 0.5	0.6 to 1.2	1.3 to 2.0	2.1 to 4.0	>4.0	**Arithmetic Averages (mg/l)**	**Analyses Medians (mg/l)**	**Category Median (mg/l)**
Blanco	4	4	0	0	0	0	0.2	0.3	—
Percent Distribution By Category	100	100	—	—	—	—	—	—	—
Range in Analyses	—	0.1-0.4	0	0	0	0	—	—	—
Arithmetic Averages	—	0.2	0	0	0	0	0.2	—	—
Analyses Medians	—	0.25	0	0	0	0	—	0.3	—
Category Medians	—	0.25	0	0	0	0	—	—	0.3

Notes: None Exceed Secondary Standard MCL of 2.0 mg/l, Primary Standard MCL of 4.0 mg/l, and Regional Average of 1.2 mg/l.

The following table provides the distribution of fluoride concentrations by range in concentration Categories, averages, and medians, for the Lower Trinity aquifer.

County(s) and Other	Number of Analyses	Distribution By Ranges in Concentration Categories in Milligrams Per Liter (mg/l)					Average and Median Concentrations		
		0.0 to 0.5	0.6 to 1.2	1.3 to 2.0	2.1 to 4.0	>4.0	Arithmetic Averages (mg/l)	Analyses Medians (mg/l)	Category Median (mg/l)
Bandera	5	0	0	2	3	0	2.4	2.4	—
Hays	8	4	2	1	1	0	0.7	1.3	—
Kendall	6	0	2	4	0	0	1.5	1.6	—
Kerr	8	0	4	4	0	0	1.3	1.3	—
Travis	68	15	13	12	20	8	1.9	2.7	—
Totals	**95**	**19**	**21**	**23**	**24**	**8**	**1.8**	2.7	—
Percent Distribution	100	20.0	22.1	24.2	25.3	8.4	—	—	—
By Categories									
Range in Analyses	—	0.0-0.4	0.6-1.2	1.3-2.0	2.1-3.9	4.2-5.3	—	—	—
Arithmetic Averages	—	0.2	0.9	1.6	3.0	4.6	1.8	—	—
Analyses Medians	—	0.20	0.90	1.65	3.00	4.75	—	1.8	—
Category Medians	—	0.25	0.90	1.65	3.05	4.75	—	—	1.8

Notes: 33.7% Exceed Secondary Standard MCL of 2.0 mg/l.
8.4% Exceed Primary Standard MCL of 4.0 mg/l.
57.9% Exceed Regional Average of 1.2 mg/l.

The following table provides the distribution of fluoride concentrations by range in concentration Categories, averages, and medians, for the Middle Trinity aquifer.

		Distribution By Ranges in Concentration Categories in Milligrams Per Liter (mg/l)					Average and Median Concentrations		
County(s) and Other	Number of Analyses	0.0 to 0.5	0.6 to 1.2	1.3 to 2.0	2.1 to 4.0	>4.0	Arithmetic Averages (mg/l)	Analyses Medians (mg/l)	Category Median (mg/l)
Bandera	13	0	0	0	10	3	3.2	3.6	—
Blanco	22	12	3	3	3	1	1.0	2.1	—
Comal	8	6	2	0	0	0	0.4	0.7	—
Hays	36	10	7	4	15	0	1.0	3.6	—
Gillespie	22	18	3	1	0	0	0.5	0.7	—
Kendall	65	27	12	14	9	3	1.3	2.6	—
Kerr	28	0	4	23	1	0	1.5	1.5	—
Travis	70	29	12	7	10	12	1.8	3.6	—
Total	**264**	**102**	**43**	**52**	**48**	**19**	**1.5**	**3.5**	—
Percent Distribution	100	38.6	16.3	19.7	18.2	7.2	—	—	—
By Categories									
Range in Analyses	—	0.0-0.5	0.6-1.2	1.3-2.0	2.1-3.9	4.1-7.0	—	—	—
Arithmetic Averages	—	0.3	0.9	1.7	2.8	5.0	1.5	—	—
Analyses Medians	—	0.25	0.90	1.65	3.00	5.55	—	1.5	—
Category Medians	—	0.25	0.90	1.65	3.05	5.55	—	—	1.5

Notes: 25.4% Exceed Secondary Standard MCL of 2.0 mg/l.
7.2% Exceed Primary Standard MCL of 4.0 mg/l.
45.1% Exceed REgional Average of 1.2 mg/l.

The following table provides the distribution of fluoride concentrations by range in concentration Categories, averages, and medians, for the Upper Trinity aquifer.

County(s) and Other	Number of Analyses	Distribution By Ranges in Concentration Categories in Milligrams Per Liter (mg/l)					Average and Median Concentrations		
		0.0 to 0.5	0.6 to 1.2	1.3 to 2.0	2.1 to 4.0	>4.0	Arithmetic Averages (mg/l)	Analyses Medians (mg/l)	Category Median (mg/l)
Bandera	16	4	3	4	3	2	1.7	2.4	—
Blanco	16	7	5	1	3	0	1.0	1.6	—
Hays	25	12	2	5	5	1	1.3	2.2	—
Kendall	12	4	3	1	4	0	1.3	1.7	—
Kerr	4	1	1	0	2	0	1.8	2.0	—
Medina	7	7	0	0	0	0	0.1	0.1	—
Travis	48	17	13	2	12	4	1.5	2.8	—
Totals	**128**	**52**	**27**	13	29	7	1.4	2.8	—
Percent Distribution	100	40.6	21.1	10.2	22.6	5.5	—	—	—
By Categories									
Range in Analyses	—	0.0-0.5	0.6-1.2	1.3-2.0	2.1-4.0	4.3-5.5	—	—	—
Arithmetic Averages	—	0.3	0.9	1.6	2.9	4.7	1.4	—	—
Analyses Medians	—	0.25	0.90	1.65	3.05	4.90	—	1.4	—
Category Medians	—	0.25	0.90	1.65	3.05	4.90	—	—	1.4

Notes: 28.1% Exceed Secondary Standard MCL of 2.0 mg/l.
5.5% Exceed Primary Standard MCL of 4.0 mg/l.
38.3% Exceed Regional Average of 1.2 mg/l.

The following table provides the distribution of fluoride concentrations by range in concentration Categories, averages, and medians, for the Edwards Plateau aquifer.

		Distribution By Ranges in Concentration Categories in Milligrams Per Liter (mg/l)					Average and Median Concentrations		
County(s) and Other	Number of Analyses	0.0 to 0.5	0.6 to 1.2	1.3 to 2.0	2.1 to 4.0	>4.0	Arithmetic Averages (mg/l)	Analyses Medians (mg/l)	Category Median (mg/l)
Bandera	12	12	0	0	0	0	0.1	0.1	—
Gillespie	85	81	4	0	0	0	0.3	0.5	—
Kerr	3	3	0	0	0	0	0.4	0.4	—
Totals	**100**	**96**	**4**	**0**	**0**	**0**	**0.3**	**0.4**	—
Percent Distribution	100	96.0	4.0	0	0	0	—	—	—
By Categories									
Range in Analyses	—	0.0-0.5	0.6-0.8	0	0	0	—	—	—
Arithmetic Averages	—	0.3	0.7	0	0	0	0.3	—	—
Analyses Medians	—	0.25	0.70	0	0	0	—	0.3	—
Category Medians	—	0.25	0.90	0	0	0	—	—	0.3

Notes: None Exceed Secondary Standard MCL of 2.0 mg/l, Primary Standard MCL of 4.0 mg/l and Regional Average of 1.2 mg/l.

APPENDIX C3

Distribution of Sulfate Concentrations by Range in Concentration Categories, Averages and Medians for the Paleozoidc and Cretaceous Aquifers

The following table provides the distribution of sulfate concentrations by range in concentration Categories, averages, and medians, for the Hickory aquifer.

		Distribution By Ranges in Concentration Categories in Milligrams Per Liter (mg/l)					Average and Median Concentrations		
County(s) and Other	Number of Analyses	<4 to 99	100 to 203	204 to 250	251-300	>300	Arithmetic Averages (mg/l)	Analyses Medians (mg/l)	Category Median (mg/l)
Blanco and Gillespie	48	42	5	0	1	0	55	137	—
Percent Distribution	100	87.5	10.4	0	2.1	0	—	—	—
By Categories									
Range in Analyses	—	7-92	100-190	0	267	0	—	—	—
Arithmetic Averages	—	41	130	0	267	0	55	—	—
Analyses Medians	—	49.5	145.0	0	267	0	—	64	—
Category Medians	—	51.0	151.5	0	267		—	—	66

Notes: None Exceed Secondary Standard MCL of 300 mg/l.
2.1% Exceed Regional Average of 203 mg/l.

The following table provides the distribution of sulfate concentrations by range in concentration Categories, averages, and medians, for the Mid-Cambrian aquifer.

County(s) and Other	Number of Analyses	Distribution By Ranges in Concentration Categories in Milligrams Per Liter (mg/l)					Average and Median Concentrations		
		<4 to 99	100 to 203	204 to 250	251-300	>300	Arithmetic Averages (mg/l)	Analyses Medians (mg/l)	Category Median (mg/l)
Blanco and Gillespie	33	32	1	0	0	0	30	55	—
Percent Distribution	100	97.0	3.0	0	0	0	—	—	—
By Category									
Range in Analyses	—	7-68	103	0	0	0	—	—	—
Arithmetic Averages	—	28	103	0	0	0	30	—	—
Analyses Medians	—	37.5	103	0	0	0	—	39	—
Category Medians	—	51.0	103	0	0	0	—	—	53

Notes: None Exceed Secondary Standard MCL of 300 mg/l.
None Exceed Regional Average of 203 mg/l.

The following table provides the distribution of sulfate concentrations by range in concentration Categories, averages, and medians, for the Ellenburger-San Saba aquifer.

County(s) and Other	Number of Analyses	Distribution By Ranges in Concentration Categories in Milligrams Per Liter (mg/l)					Average and Median Concentrations		
		<4 to 99	100 to 203	204 to 250	251-300	>300	Arithmetic Averages (mg/l)	Analyses Medians (mg/l)	Category Median (mg/l)
Blanco and Gillespie	50	50	0	0	0	0	35	50	—
Percent Distribution	100	100	0	0	0	0	—	—	—
By Category									
Range in Analyses	—	8-91	0	0	0	0	—	—	—
Arithmetic Averages	—	35	0	0	0	0	35	—	—
Analyses Medians	—	49.5	0	0	0	0	—	50	—
Category Medians	—	51.0	0	0	0	0	—	—	51

Notes: None Exceed Secondary Standard MCL of 300 mg/l and Regional Average of 203 mg/l.

The following table provides the distribution of sulfate concentrations by range in concentration Categories, averages, and medians, for the Marble Falls aquifer.

		Distribution By Ranges in Concentration Categories in Milligrams Per Liter (mg/l)					Average and Median Concentrations		
County(s) and Other	Number of Analyses	<4 to 99	100 to 203	204 to 250	251-300	>300	Arithmetic Averages (mg/l)	Analyses Medians (mg/l)	Category Median (mg/l)
Blanco	15	14	1	0	0	0	30	74	—
Percent Distribution	100	93.3	6.7	0	0	0	—	—	—
By Category									
Range in Analyses	—	11-45	136	0	0	0	—	—	—
Arithmetic Averages	—	22	136	—	—	—	30	—	—
Analyses Medians	—	28.0	136	—	—	—	—	35	—
Category Medians	—	51.0	136	—	—	—	—	—	57

Notes: None Exceed Secondary Standard MCL of 300 mg/l and Regional Average of 203 mg/l.

The following table provides the distribution of sulfate concentrations by range in concentration Categories, averages, and medians, for the Lower Trinity aquifer.

		Distribution By Ranges in Concentration Categories in Milligrams Per Liter (mg/l)					Average and Median Concentrations		
County(s) and Other	**Number of Analyses**	<4 to 99	100 to 203	204 to 250	251-300	>300	Arithmetic Averages (mg/l)	Analyses Medians (mg/l)	Category Median (mg/l)
Bandera	5	4	1	0	0	0	69	84	—
Hays	8	5	0	0	0	3	286	535	—
Kendall	6	0	3	1	1	1	229	248	—
Kerr	8	6	2	0	0	0	68	73	—
Travis	67	23	7	3	9	25	304	903	—
Totals	**94**	**38**	**13**	**4**	**10**	**29**	**265**	**903**	—
Percent Distribution	100	40.4	13.8	4.3	10.6	30.9	—	—	—
By Category									
Range in Analyses	—	15-99	105-200	217-224	257-287	306-1790	—	—	—
Arithmetic Averages	—	41	145	221	272	617	265	—	—
Analyses Medians	—	57.0	152.5	220.5	272.0	1,048	—	405	—
Category Medians	—	51.0	151.5	227.5	275.5	1,048	—	—	404

Notes: 30.9% Exceed Secondary Standard MCL of 300 mg/l.
45.8% Exceed Regional Average of 203 mg/l.

The following table provides the distribution of sulfate concentrations by range in concentration Categories, averages, and medians, for the Middle Trinity aquifer.

County(s) and Other	Number of Analyses	Distribution By Ranges in Concentration Categories in Milligrams Per Liter (mg/l)					Average and Median Concentrations		
		<4 to 99	100 to 203	204 to 250	251-300	>300	Arithmetic Averages (mg/l)	Analyses Medians (mg/l)	Category Median (mg/l)
Bandera	13	0	6	0	1	6	386	860	—
Blanco	36	26	3	1	0	6	268	1,456	—
Comal	8	8	0	0	0	0	27	48	—
Hays	36	14	4	2	4	12	350	704	—
Gillespie	22	21	1	0	0	0	33	55	—
Kendall	65	36	16	4	1	8	152	852	—
Kerr	30	17	12	0	0	1	90	281	—
Travis	71	35	8	5	1	22	423	1,683	—
Totals	**281**	**157**	**50**	**12**	**7**	**55**	**252**	**1,681**	—
Percent Distribution	100	55.8	17.8	4.3	2.5	19.6	—	—	—
By Category									
Range in Analyses	—	2-96	101-197	205-245	253-299	310-3,360	—	—	—
Arithmetic Averages	—	33	148	221	273	976	252	—	—
Analyses Medians	—	49.0	149.0	225.0	276.0	1,835	—	430	—
Category Medians	—	51.0	151.5	227.0	275.5	1,835	—	—	431

Notes: 19.6% Exceed Secondary Standard MCL of 300 mg/l.
16.4% Exceed Regional Average of 203 mg/l.

The following table provides the distribution of sulfate concentrations by range in concentration Categories, averages, and medians, for the Upper Trinity aquifer.

		Distribution By Ranges in Concentration Categories in Milligrams Per Liter (mg/l)					Average and Median Concentrations		
County(s) and Other	Number of Analyses	<4 to 99	100 to 203	204 to 250	251-300	>300	Arithmetic Averages (mg/l)	Analyses Medians (mg/l)	Category Median (mg/l)
Blanco and Bandera	26	7	2	1	1	15	802	1,110	—
Blanco	23	16	1	0	0	6	353	930	—
Hays	26	15	3	1	2	5	365	968	—
Kendall	12	4	2	2	0	4	260	350	—
Kerr	6	2	0	0	0	4	867	1,023	—
Medina	8	7	0	0	0	1	69	218	—
Travis	48	21	19	4	0	4	157	1,187	—
Totals	**149**	**72**	**27**	**8**	**3**	**39**	**360**	**1,187**	—
Percent Distribution	100	48.3	18.1	5.4	2.0	26.2	—	—	—
By Category									
Range in Analyses	—	4-99	100-202	206-244	251-279	327-2370	—	—	—
Arithmetic Averages	—	29	134	227	263	1,162	360	—	—
Analyses Medians	—	51.5	151.0	225.0	265.0	1,349	—	423	—
Category Medians	—	51.0	151.5	227.0	275.5	1,349	—	—	423

Notes: 26.2% Exceed Secondary Standard of 300 mg/l.
33.6% Exceed Regional Average of 203 mg/l.

The following table provides the distribution of sulfate concentrations by range in concentration Categories, averages, and medians, for the Edwards Plateau aquifer.

		Distribution By Ranges in Concentration Categories in Milligrams Per Liter (mg/l)					Average and Median Concentrations		
County(s) and Other	**Number of Analyses**	**<4 to 99**	**100 to 203**	**204 to 250**	**251-300**	**>300**	**Arithmetic Averages (mg/l)**	**Analyses Medians (mg/l)**	**Category Median (mg/l)**
Bandera	17	17	0	0	0	0	7	12	—
Gillespie	85	84	1	0	0	0	16	66±	—
Kerr	4	4	0	0	0	0	11	12	—
Totals	**106**	**105**	**1**	**0**	**0**	**0**	**14**	**66±**	—
Percent Distribution	100	99.0	1.0	0	0	0	—	—	—
By Category									
Range in Analyses	—	<4-70	130	0	0	0	—	—	—
Arithmetic Average	—	13±	130	0	0	0	14	—	—
Analyses Medians	—	36.0±	130	0	0	0	—	37	—
Category Medians	—	51.0	130	0	0	0	—	—	52

Notes: None Exceed Secondary Standard
MCL of 300 mg/l and Regional Average of 203 mg/l.

APPENDIX D

Estimated 1985 Ground-Water Pumpage by County, by Use Catagory, by Aquifer, in Acre-Feet and Estimated Number of Large-Capacity Wells Used in 1985 in the Hill Country Study Area, Texas

Estimated 1985 Ground-Water Pumpage by Use Category by Aquifer in Acre-Feet and Estimated Number of Large-Capacity Wells Used in 1985 in Bandera County

Use Category	Edwards Plateau Aquifer	Trinity Group Aquifers	Marble Falls Aquifer	Ellenburger-San Saba Aquifer	Mid-Cambrian Aquifer	Hickory Aquifer	Precambrian Aquifer	Total Pumpage	Percent	No. Wells Used
Major Public Supply •Bandera	—	199	—	—	—	—	—	199	13.3	3
Other Public Supply	—	165	—	—	—	—	—	165	11.0	14
Rural Domestic Supply	47	743	—	—	—	—	—	790	52.8	Unknown
Manufacturing	—	—	—	—	—	—	—	—	—	—
Power	—	—	—	—	—	—	—	—	—	—
Mining	—	24	—	—	—	—	—	24	1.6	Unknown
Irrigation	—	89	—	—	—	—	—	89	6.0	12
Livestock	23	206	—	—	—	—	—	229	15.3	Unknown
Total Pumpage and Wells Used	**70**	**1,426**	—	—	—	—	—	**1,496**	**100.0**	**29**
Percent	4.7	95.3	—	—	—	—	—	100.0	—	—

Estimated 1985 Ground-Water Pumpage by Use Category by Aquifer in Acre-Feet and Estimated Number of Large-Capacity Wells Used in 1985 in Blanco County

Use Category	Edwards Plateau Aquifer	Trinity Group Aquifers	Marble Falls Aquifer	Ellenburger-San Saba Aquifer	Mid-Cambrian Aquifer	Hickory Aquifer	Precambrian Aquifer	Total Pumpage	Percent	No. Wells Used
Major Public Supply •Johnson City[1]	—	—	—	152	—	—	—	152	13.9	2
Other Public Supply	—	15	—	—	—	—	—	15	1.4	2
Rural Domestic Supply	—	253	5	42	17	11	4	332	30.3	Unknown
Manufacturing	—	—	—	—	—	—	—	—	—	—
Power	—	—	—	—	—	—	—	—	—	—
Mining	—	—	—	—	—	—	—	—	—	—
Irrigation	—	64	—	150	—	40	—	254	23.2	14[2]
Livestock	—	236	6	54	21	19	5	341	31.2	Unknown
Total Pumpage and Wells Used	—	**568**	11	**398**	**38**	**70**	**9**	**1,094**	**100.0**	**18**
Percent	—	51.9	1.0	36.4	3.5	6.4	0.8	100.0	—	—

[1] Also used 58 acre-feet of surface water from the Pedernales River.

[2] Includes approximately 6 Trinity Group, 6 Ellenburger-San Saba and 2 Hickory wells.

Estimated 1985 Ground-Water Pumpage by Use Category by Aquifer in Acre-Feet and Estimated Number of Large-Capacity Wells Used in 1985 in Comal County

Use Category	Edwards Plateau Aquifer	Trinity Group Aquifers	Marble Falls Aquifer	Ellenburger-San Saba Aquifer	Mid-Cambrian Aquifer	Hickory Aquifer	Precambrian Aquifer	Total Pumpage	Percent	No. Wells Used
Major Public Supply •Canyon Lake Forest Utility	—	178	—	—	—	—	—	178	13.0	4
•General Utilities & Development Co.	—	161	—	—	—	—	—	161	11.8	6
•Haskin Water Supply	—	93	—	—	—	—	—	93	6.8	99
•W&W Water Co.	—	292	—	—	—	—	—	292	21.4	14
Other Public Supply	—	454	—	—	—	—	—	454	33.2	57
Rural Domestic Supply	—	55	—	—	—	—	—	55	4.0	Unknown
Manufacturing	—	—	—	—	—	—	—	—	—	—
Power	—	—	—	—	—	—	—	—	—	—
Mining	—	—	—	—	—	—	—	—	—	—
Irrigation	—	—	—	—	—	—	—	—	—	—
Livestock	—	134	—	—	—	—	—	134	9.8	Unknown
Total Pumpage and Wells Used	**—**	**1,367**	**—**	**—**	**—**	**—**	**—**	**1,367**	**100.0**	**90**
Percent	—	100.0	—	—	—	—	—	100.0	—	—

Estimated 1985 Ground-Water Pumpage by Use Category by Aquifer in Acre-Feet and Estimated Number of Large-Capacity Wells Used in 1985 in Gillespie County

Use Category	Edwards Plateau Aquifer	Trinity Group Aquifers	Marble Falls Aquifer	Ellenburger-San Saba Aquifer	Mid-Cambrian Aquifer	Hickory Aquifer	Precambrian Aquifer	Total Pumpage	Percent	No. Wells Used
Major Public Supply										
•Fredericksburg	—	[1]	—	1,828	—	203	—	2,031	39.6	8[2]
Other Public Supply	7	7	—	39	—	29	3	85	1.7	15[3]
Rural Domestic Supply	287	336	7	99	8	82	6	825	16.1	Unknown
Manufacturing	—	—	—	—	—	—	—	—	—	—
Power	—	—	—	—	—	—	—	—	—	—
Mining	—	—	—	16	—	—	—	16	0.3	Unknown
Irrigation	103	890	—	376	—	342	—	1,711	33.4	46[4]
Livestock	160	182	5	55	5	45	4	456	8.9	Unknown
Total Pumpage and Wells Used	**557**	**1,415**	**12**	**2,413**	**13**	**701**	**13**	**5,124**	**100.0**	**69**
Percent	10.8	27.6	0.2	47.1	0.3	13.7	0.3	100.0	—	—

[1] Very small amount which is included in Hickory aquifer pumpage (203 acre-feet).

[2] Includes 5 Ellenburger-San Saba wells, 2 Hickory wells and 1 Trinity Group-Hickory well.

[3] Includes 1 Edwards Plateau, 1 Trinity Group, 5 Ellenburger-San Saba, 7 Hickory and 1 Precambrian wells.

[4] Includes 3 Edwards Plateau, 24 Trinity Group, 10 Ellenburger-San Saba and 9 Hickory Wells.

Estimated 1985 Ground-Water Pumpage by Use Category by Aquifer in Acre-Feet and Estimated Number of Large-Capacity Wells Used in 1985 in Hays County

Use Category	Edwards Plateau Aquifer	Trinity Group Aquifers	Marble Falls Aquifer	Ellenburger-San Saba Aquifer	Mid-Cambrian Aquifer	Hickory Aquifer	Precambrian Aquifer	Total Pumpage	Percent	No. Wells Used
Major Public Supply										
•Dripping Springs WSC	—	294	—	—	—	—	—	294	16.5	2
•Wimberly WSC	—	363	—	—	—	—	—	363	20.4	5
•Woodcreek Utilities	—	493	—	—	—	—	—	493	27.7	3
Other Public Supply	—	24	—	—	—	—	—	24	1.4	5
Rural Domestic Supply	—	300	—	—	—	—	—	300	16.9	Unknown
Manufacturing	—	—	—	—	—	—	—	—	—	—
Power	—	—	—	—	—	—	—	—	—	—
Mining	—	—	—	—	—	—	—	—	—	—
Irrigation	—	—	—	—	—	—	—	—	—	—
Livestock	—	303	—	—	—	—	—	303	17.1	Unknown
Total Pumpage and Wells Used	—	**1,777**	—	—	—	—	—	**1,777**	**100.0**	**15**
Percent	—	100.0	—	—	—	—	—	100.0	—	—

Estimated 1985 Ground-Water Pumpage by Use Category by Aquifer in Acre-Feet and Estimated Number of Large-Capacity Wells Used in 1985 in Kendall County

Use Category	Edwards Plateau Aquifer	Trinity Group Aquifers	Marble Falls Aquifer	Ellenburger-San Saba Aquifer	Mid-Cambrian Aquifer	Hickory Aquifer	Precambrian Aquifer	Total Pumpage	Percent	No. Wells Used
Major Public Supply										
•Boerne[1]	–	336	—	—	—	—	—	336	16.8	8
•Comfort	—	217	—	—	—	—	—	217	10.8	5
Other Public Supply	—	129	—	—	—	—	—	129	6.5	13
Rural Domestic Supply	—	856	—	—	—	—	—	856	42.8	Unknown
Manufacturing	—	5	—	—	—	—	—	5	0.2	1
Power	—	—	—	—	—	—	—	—	—	—
Mining	—	—	—	—	—	—	—	—	—	—
Irrigation	—	132	—	—	—	—	—	132	6.6	12
Livestock	—	326	—	—	—	—	—	326	16.3	Unknown
Total Pumpage and Wells Used	—	**2,001**	—	—	—	—	—	**2,001**	**100.0**	**39**
Percent	—	100.0	—	—	—	—	—	100.0	—	—

[1] Also used 451 acre-feet of surface water from a city lake on Cibolo Creek.

Estimated 1985 Ground-Water Pumpage by Use Category by Aquifer in Acre-Feet and Estimated Number of Large-Capacity Wells Used in 1985 in Kerr County

Use Category	Edwards Plateau Aquifer	Trinity Group Aquifers	Marble Falls Aquifer	Ellenburger-San Saba Aquifer	Mid-Cambrian Aquifer	Hickory Aquifer	Precambrian Aquifer	Total Pumpage	Percent	No. Wells Used
Major Public Supply										
•Kerrville[1]	–	872	—	—	—	—	—	872	25.3	13
•Ingram	—	376	—	—	—	—	—	376	10.9	4
•Kerrville South Water Co.	—	235	—	—	—	—	—	235	6.8	4
•Hill Country Utilities	—	197	—	—	—	—	—	197	5.7	21
Other Public Supply	—	431	—	—	—	—	—	431	12.5	36
Rural Domestic Supply	252	470	—	—	—	—	—	722	21.0	Unknown
Manufacturing	—	—	—	—	—	—	—	—	—	—
Power	—	—	—	—	—	—	—	—	—	—
Mining	—	81	—	—	—	—	—	81	2.4	Unknown
Irrigation	—	204	—	—	—	—	—	204	5.9	14
Livestock	213	114	—	—	—	—	—	327	9.5	Unknown
Total Pumpage and Wells Used	**465**	**2,980**	—	—	—	—	—	**3,445**	**100.0**	**92**
Percent	13.5	86.5	—	—	—	—	—	100	—	—

[1] Also used 2,870 acre-feet of surface water from Quinlan Creek and the Guadalupe River.

Estimated 1985 Ground-Water Pumpage by Use Category by Aquifer in Acre-Feet and Estimated Number of Large-Capacity Wells Used in 1985 in Medina County

Use Category	Edwards Plateau Aquifer	Trinity Group Aquifers	Marble Falls Aquifer	Ellenburger-San Saba Aquifer	Mid-Cambrian Aquifer	Hickory Aquifer	Precambrian Aquifer	Total Pumpage	Percent	No. Wells Used
Major Public Supply	—	—	—	—	—	—	—	—	—	—
Other Public Supply	—	5	—	—	—	—	—	5	5.0	4
Rural Domestic Supply	—	78	—	—	—	—	—	78	78.0	Unknown
Manufacturing	—	—	—	—	—	—	—	—	—	—
Power	—	—	—	—	—	—	—	—	—	—
Mining	—	—	—	—	—	—	—	—	—	Unknown
Irrigation	—	—	—	—	—	—	—	—	—	—
Livestock	—	17	—	—	—	—	—	17	17.0	Unknown
Total Pumpage and Wells Used	—	**100**	—	—	—	—	—	**100**	**100.0**	**4**
Percent	—	100.0	—	—	—	—	—	100.0	—	—

Estimated 1985 Ground-Water Pumpage by Use Category by Aquifer in Acre-Feet and Estimated Number of Large-Capacity Wells Used in 1985 in Travis County

Use Category	Edwards Plateau Aquifer	Trinity Group Aquifers	Marble Falls Aquifer	Ellenburger-San Saba Aquifer	Mid-Cambrian Aquifer	Hickory Aquifer	Precambrian Aquifer	Total Pumpage	Percent	No. Wells Used
Major Public Supply										
•Apache Shores, Inc.	—	125	—	—	—	—	—	125	5.4	4
Other Public Supply	—	158	6	—	—	—	—	164	7.0	17[1]
Rural Domestic Supply	—	1,938	—	—	—	—	—	1,938	83.0	Unknown
Manufacturing	—	—	—	—	—	—	—	—	—	—
Power	—	—	—	—	—	—	—	—	—	—
Mining	—	—	—	—	—	—	—	—	—	—
Irrigation	—	—	—	—	—	—	—	—	—	—
Livestock	—	108	—	—	—	—	—	108	4.6	Unknown
Total Pumpage and Wells Used	—	**2,329**	**6**	—	—	—	—	**2,335**	**100.0**	**21**
Percent	—	99.7	0.3	—	—	—	—	100.0	—	—

[1] Includes 15 Trinity Group and 2 Marble Falls wells.

APPENDIX E

Estimated Water Use in 1980 and 1985 by County

(Texas Water Development Board, 1988)

Estimated Water Use in 1980 and 1985 in Bandera County, Texas

	Estimated 1980 Water Use in Acre-Feet			Estimated 1985 Water Use in Acre-Feet		
Water Use Category	**Ground Water**	**Surface Water**	**Total Use**	**Ground Water**	**Surface Water**	**Total Use**
Public Supply and Rural Domestic	910	-0-	910	1,154	18	1,172
Manufacturing	8	-0-	8	-0-	-0-	-0-
Power	-0-	-0-	-0-	-0-	-0-	-0-
Mining	-0-	-0-	-0-	24	-0-	24
Irrigation	99	439	538	89	160	249
Livestock	303	73	376	229	55	284
County Total Water Use	**1,320**	**512**	**1,832**	**1,496**	**233**	**1,729**

Estimated Water Use in 1980 and 1985 in Blanco County, Texas

	Estimated 1980 Water Use in Acre-Feet			Estimated 1985 Water Use in Acre-Feet		
Water Use Category	**Ground Water**	**Surface Water**	**Total Use**	**Ground Water**	**Surface Water**	**Total Use**
Public Supply and Rural Domestic	350	386	736	499	310	809
Manufacturing	-0-	1	1	-0-	1	1
Power	-0-	-0-	-0-	-0-	-0-	-0-
Mining	-0-	-0-	-0-	-0-	-0-	-0-
Irrigation	149	76	225	254	45	299
Livestock	387	87	474	341	85	426
County Total Water Use	**886**	**550**	**1,436**	**1,094**	**441**	**1,535**

Estimated Water Use in 1980 and 1985 in Comal County, Texas

	Estimated 1980 Water Use in Acre-Feet			Estimated 1985 Water Use in Acre-Feet		
Water Use Category	**Ground Water**	**Surface Water**	**Total Use**	**Ground Water**	**Surface Water**	**Total Use**
Public Supply and Rural Domestic	920	-0-	920	1,233	-0-	1,233
Manufacturing	-0-	-0-	-0-	-0-	-0-	-0-
Power	-0-	-0-	-0-	-0-	-0-	-0-
Mining	-0-	-0-	-0-	-0-	-0-	-0-
Irrigation	30	56	86	-0-	-0-	-0-
Livestock	167	41	208	134	33	167
County Total Water Use	**1,117**	**97**	**1,214**	**1,367**	**33**	**1,400**

Estimated Water Use in 1980 and 1985 in Gillespie County, Texas

	Estimated 1980 Water Use in Acre-Feet			Estimated 1985 Water Use in Acre-Feet		
Water Use Category	Ground Water	Surface Water	Total Use	Ground Water	Surface Water	Total Use
Public Supply and Rural Domestic	2,273	-0-	2,273	2,785	–0–	2,785
Manufacturing	505	80	585	156	117	273
Power	-0-	-0-	-0-	-0-	–0–	–0–
Mining	-0-	-0-	-0-	16	–0–	16
Irrigation	800	880	1,680	1,711	48	1,859
Livestock	664	497	1,161	456	456	912
County Total Water Use	**4,242**	**1,457**	**5,699**	**5,124**	**721**	**5,845**

Estimated Water Use in 1980 and 1985 Hays County, Texas

Water Use Category	Estimated 1980 Water Use in Acre-Feet			Estimated 1985 Water Use in Acre-Feet		
	Ground Water	Surface Water	Total Use	Ground Water	Surface Water	Total Use
Public Supply and Rural Domestic	723	-0-	723	1,474	-0-	1,474
Manufacturing	-0-	-0-	-0-	-0-	-0-	-0-
Power	-0-	-0-	-0-	-0-	-0-	-0-
Mining	-0-	-0-	-0-	-0-	-0-	-0-
Irrigation	-0-	42	42	-0-	54	54
Livestock	282	57	339	303	62	365
County Total Water Use	**1,005**	**99**	**1,104**	**1,777**	**116**	**1,893**

Estimated Water Use in 1980 and 1985 in Kendall County, Texas

Water Use Category	Estimated 1980 Water Use in Acre-Feet			Estimated 1985 Water Use in Acre-Feet		
	Ground Water	Surface Water	Total Use	Ground Water	Surface Water	Total Use
Public Supply and Rural Domestic	1,103	381	1,484	1,538	451	1,989
Manufacturing	4	3	7	5	-0-	5
Power	-0-	-0-	-0-	-0-	-0-	-0-
Mining	-0-	-0-	-0-	-0-	-0-	-0-
Irrigation	200	336	536	132	18	150
Livestock	441	98	539	326	80	406
County Total Water Use	**1,748**	**818**	**2,566**	**2,001**	**549**	**2,550**

Estimated Water Use in 1980 and 1985 in Kerr County, Texas

	Estimated 1980 Water Use in Acre-Feet			Estimated 1985 Water Use in Acre-Feet		
Water Use Category	Ground Water	Surface Water	Total Use	Ground Water	Surface Water	Total Use
Public Supply and Rural Domestic	4,764	96	4,860	2,831	2,864	5,695
Manufacturing	19	-0-	19	2	5	7
Power	-0-	-0-	-0-	-0-	-0-	-0-
Mining	-0-	-0-	-0-	81	-0-	81
Irrigation	500	784	1,284	204	996	1,200
Livestock	433	102	535	327	80	407
County Total Water Use	**5,716**	**982**	**6,698**	**3,445**	**3,945**	**7,390**

Estimated Water Use in 1980 and 1985 in Medina County, Texas

	Estimated 1980 Water Use in Acre-Feet			Estimated 1985 Water Use in Acre-Feet		
Water Use Category	Ground Water	Surface Water	Total Use	Ground Water	Surface Water	Total Use
Public Supply and Rural Domestic	77	-0-	77	83	-0-	83
Manufacturing	-0-	-0-	-0-	-0-	-0-	-0-
Power	-0-	-0-	-0-	-0-	-0-	-0-
Mining	-0-	-0-	-0-	-0-	-0-	-0-
Irrigation	-0-	-0-	-0-	-0-	-0-	-0-
Livestock	30	150	180	17	154	171
County Total Water Use	**107**	**150**	**257**	**100**	**154**	**254**

Estimated Water Use in 1980 and 1985 in Travis County, Texas

	Estimated 1980 Water Use in Acre-Feet			Estimated 1985 Water Use in Acre-Feet		
Water Use Category	**Ground Water**	**Surface Water**	**Total Use**	**Ground Water**	**Surface Water**	**Total Use**
Public Supply and Rural Domestic	1,555	2,426	3,981	2,227	5,405	7,632
Manufacturing	-0-	-0-	-0-	-0-	-0-	-0-
Power	-0-	-0-	-0-	-0-	-0-	-0-
Mining	-0-	-0-	-0-	-0-	-0-	-0-
Irrigation	-0-	-0-	-0-	-0-	-0-	-0-
Livestock	132	116	248	108	94	202
County Total Water Use	**1,687**	**2,542**	**4,229**	**2,335**	**5,499**	**7,834**

APPENDIX F

Projected Water Demands for 1990, 2000, and 2010 by County

(Texas Water Development Board, 1988)

Projected Water Demands For 1990, 2000, and 2010 in Bandera County, Texas

Water Demand Catagory	**Projected Water Demands in Acre-Feet** **1990**	**2000**	**2010**
Public Supply and Rural Domestic	2,666	3,429	3,966
Manufacturing	12	15	17
Power	-0-	-0-	-0-
Mining	-0-	-0-	-0-
Irrigation	213	217	219
Livestock	440	506	506
County Total Water Demands	**3,331**	**4,167**	**4,708**

Projected Water Demands For 1990, 2000, and 2010 in Blanco County, Texas

Water DemandCatagory	**Projected Water Demands in Acre-Feet** 1990	2000	2010
Public Supply and Rural Domestic	1,340	1,803	2,267
Manufacturing	2	2	3
Power	-0-	-0-	-0-
Mining	6	12	9
Irrigation	218	222	224
Livestock	556	639	639
County Total Water Demands	**2,122**	**2,678**	**3,142**

Projected Water Demands For 1990, 2000, and 2010 in Comal County, Texas

Water Demand Catagory	**Projected Water Demands in Acre-Feet** **1990**	**2000**	**2010**
Public Supply and Rural Domestic	1,310	1,847	2,272
Manufacturing	-0-	-0-	-0-
Power	-0-	-0-	-0-
Mining	-0-	-0-	-0-
Irrigation	116	117	119
Livestock	245	283	283
County Total Water Demands	**1,671**	**2,247**	**2,674**

Projected Water Demands For 1990, 2000, and 2010 in Gillespie County, Texas

Water Demand Catagory	Projected Water Demands in Acre-Feet 1990	2000	2010
Public Supply and Rural Domestic	3,719	4,523	5,029
Manufacturing	776	1,044	1,330
Power	-0-	-0-	-0-
Mining	6	12	9
Irrigation	1,374	1,395	1,413
Livestock	1,347	1,535	1,535
County Total Water Demands	**7,222**	**8,509**	**9,316**

Projected Water Demands For 1990, 2000, and 2010 in Hays County, Texas

Water Demand Catagory	Projected Water Demands in Acre-Feet 1990	2000	2010
Public Supply and Rural Domestic	1,273	2,035	2,828
Manufacturing	-0-	-0-	-0-
Power	-0-	-0-	-0-
Mining	-0-	-0-	-0-
Irrigation	75	77	77
Livestock	399	459	459
County Total Water Demands	**1,747**	**2,571**	**3,364**

Projected Water Demands For 1990, 2000, and 2010 in Kendall County, Texas

Water Demand Catagory	Projected Water Demands in Acre-Feet 1990	2000	2010
Public Supply and Rural Domestic	3,158	3,974	4,571
Manufacturing	11	13	17
Power	-0-	-0-	-0-
Mining	6	12	9
Irrigation	601	610	618
Livestock	630	722	722
County Total Water Demands	**4,406**	**5,331**	**5,937**

Projected Water Demands For 1990, 2000, and 2010 in Kerr County, Texas

Water Demand Catagory	Projected Water Demands in Acre-Feet		
	1990	2000	2010
Public Supply and Rural Domestic	8,425	10,793	12,467
Manufacturing	27	38	49
Power	-0-	-0-	-0-
Mining	6	12	9
Irrigation	816	828	839
Livestock	621	709	709
County Total Water Demands	**9,895**	**12,380**	**14,073**

Projected Water Demands For 1990, 2000, and 2010 in Medina County, Texas

Water Demand Catagory	Projected Water Demands in Acre-Feet		
	1990	2000	2010
Public Supply andRural Domestic	123	138	156
Manufacturing	-0-	-0-	-0-
Power	-0-	-0-	-0-
Mining	-0-	-0-	-0-
Irrigation	-0-	-0-	-0-
Livestock	214	248	248
County Total Water Demands	**337**	**386**	**404**

Projected Water Demands For 1990, 2000, and 2010 in Travis County, Texas

Water Demand Catagory	Projected Water Demands in Acre-Feet		
	1990	2000	2010
Public Supply and Rural Domestic	8,355	11,442	13,824
Manufacturing	-0-	-0-	-0-
Power	-0-	-0-	-0-
Mining	-0-	-0-	-0-
Irrigation	-0-	-0-	-0-
Livestock	248	248	248
County Total Water Demands	**8,603**	**11,690**	**14,072**