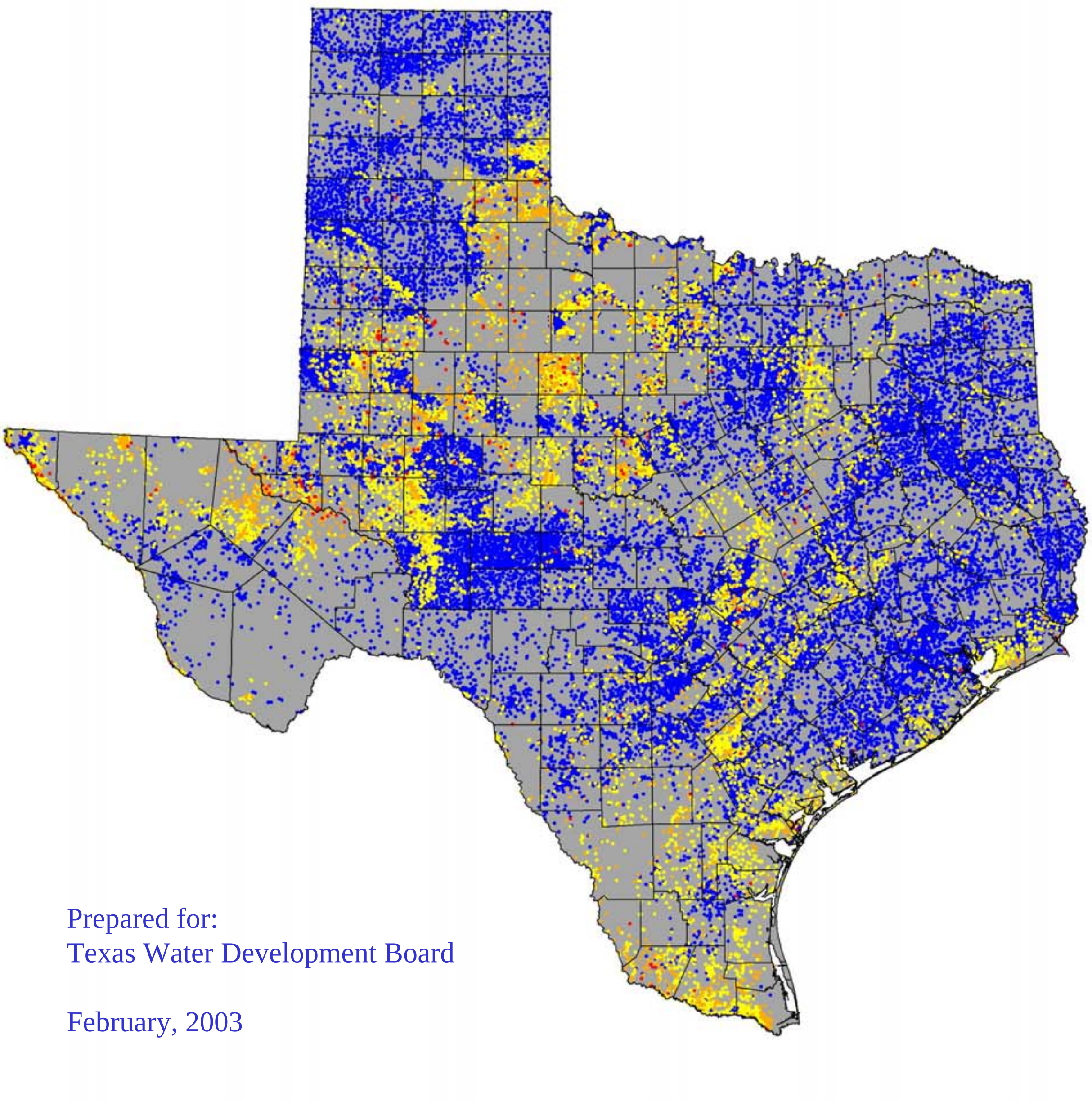
Brackish Groundwater Manual for Texas Regional Water Planning Groups



Prepared for:
Texas Water Development Board

February, 2003

LBG-GUYTON ASSOCIATES
in association with
NRS Consulting Engineers

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Brackish Groundwater in Texas
a Manual for
Texas Regional Water Planning Groups

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Executive Summary

Brackish groundwater is defined as groundwater containing between 1,000 and 10,000 milligrams per liter (mg/L) total dissolved solids (TDS). The State of Texas has a tremendous resource in brackish groundwater that can be found throughout the state, including West Texas, North-Central Texas, Central Texas, and the Southern Coastal region. Increasing water demands, increasing water rights costs, decreasing freshwater supplies, stricter drinking water standards, and more cost-effective desalination technology are paving the way for more widespread and cost-effective use of this resource. Brackish groundwater resources are important for the future development in many parts of the state where fresh ground-water supplies and new surface water supplies are limited, nonexistent or cost prohibitive. This report has been developed to assist planners in identifying and assessing potential brackish groundwater resources as well as developing preliminary cost estimates for proposed strategies. Although this report is general in nature, it can serve as a valuable tool to help identify potential brackish groundwater and aid in developing cost estimates for regional water planning groups (RWPGs) and other planning entities. However, this document is not intended to be an exhaustive resource on the subject of brackish groundwater resources and desalination of brackish groundwater in Texas, and it should be understood that any proposed desalination project will require site-specific hydrogeologic and engineering analysis.

Brackish groundwater is present in most of the major and minor aquifers in the state. In many cases, the geographical extent and volume of water available from an aquifer is significantly increased when groundwater up to 10,000 mg/L TDS is considered. However, brackish groundwater is sometimes found in the deeper, less productive portions of an aquifer, and therefore may not be as readily available as the fresh groundwater in the aquifer. The total estimated volume of brackish groundwater "in place" in Texas aquifers is over 2.5 billion acre-feet.

Improvements in membrane technology in recent years has significantly decreased the cost of brackish groundwater desalination. Recent data have shown that the cost of brackish groundwater desalination is decreasing and that improved membrane technology is still increasing the efficiency and effectiveness of the desalination process. The cost information summarized in this report indicates that the total treatment cost of brackish groundwater desalination can range from $1.50/Kgal to $2.75/Kgal. In general, it is less expensive to desalinate lower TDS groundwater than higher TDS brackish groundwater because the energy requirements for desalination of low TDS water are less than for high TDS water. Estimates of the total cost for brackish groundwater desalination should consider each component of the project including the cost of source-water production and concentrate handling.

Source-water production, concentrate disposal, and plant design should be considered simultaneously throughout project conceptualization and design because each component of the project is interrelated. Hydrogeologic and engineering components of a brackish groundwater desalination strategy are not mutually exclusive and will require coordinated planning to achieve the best results.

Brackish groundwater resources offer the State of Texas a potential source of water that has not been fully utilized in the past. Each RWPG should consider strategies that use brackish groundwater as a way of meeting future demands.

1.0 INTRODUCTION

1.1 State Water Planning

The 75th Texas Legislature initiated a long-term program known as Regional Water Planning (RWP) to evaluate the availability of water resources over a 50-year planning period. One objective of RWP is to provide planners with sufficient information to guide the development of water management plans for the State's 16 water-planning regions. The Regional Water Planning Groups (RWPGs) are responsible for developing a comprehensive regional plan every five years that resolves any issues related to the development and management of water resources. The Texas Water Development Board (TWDB) then assimilates each of the sixteen plans into a comprehensive plan for the State of Texas, ensuring that any interregional conflicts or inconsistencies are addressed.

According to the 2002 Texas State Water Plan developed by the TWDB, the demand for fresh water will continue to increase in Texas. By 2050, the population of Texas is predicted to double and the water demand is expected to increase 18% (3 million acre-feet/year increase). Desalination of seawater and brackish groundwater is becoming a more commonly sought strategy to address increasing water demands, especially municipal demands, which are projected to increase 67% by 2050.

1.2 Brackish Groundwater in Texas

Many water-bearing formations in Texas contain a large volume of brackish groundwater for which desalination may be feasible to help meet the increasing demand. Several factors may make the use of brackish water an attractive water supply alternative, including decreasing supplies of fresh groundwater and surface water, improvements in treatment technology, stricter drinking water standards, increased cost of water rights, increased competition for surface-water resources, and changes in population/demand centers. Conversely, desalination of brackish groundwater has impediments, including treatment cost, impact of brackish-water withdrawal on fresh groundwater resources, and brine disposal issues. For the purposes of this study, brackish groundwater is defined as water containing more than 1,000 milligrams per liter (mg/L) total dissolved solids (TDS) and less than 10,000 mg/L TDS.

The distribution and characteristics of brackish groundwater vary throughout Texas. To better understand the nature and distribution of brackish groundwater in Texas, it is helpful to recognize the origins of brackish groundwater.

Almost all groundwater originates as rain or snowmelt that infiltrates the soil and moves into groundwater flow systems in the underlying geologic materials. In the surface soil zones, there are numerous chemical and biological mechanisms that may alter the water quality. Typically, the TDS in rain and snow are very low, but upon infiltration, the water reacts with soils and rock minerals in the subsurface and the TDS normally increases. In particular, increases in sulfate and chloride concentrations are derived from several sources, including dissolution of gypsum, pyrite, anhydrite, or halite. Groundwater can be a mixture of waters that originate at different recharge locations and travel along different groundwater flow paths, producing unique geochemical signatures prior to mixing. In deep groundwater systems where movement is relatively slow or almost static, chloride brines may evolve. Richter and Kreitler (1986) provide a good discussion and summary of major-ion chemistries that occur in different hydrogeologic settings.

While there have been many cases of groundwater contamination from manmade sources, the biggest factor controlling regional groundwater quality is the hydrogeochemical characteristics and controls on the groundwater flow system that have occurred over long periods of time. It is important to recognize that, in general, current regional groundwater quality has been developing for hundreds, thousands, or potentially millions of years. Some factors that control the hydrogeochemistry of groundwater include the mineral composition of the aquifer material, geochemical processes, groundwater flow velocity, residence time, long-term historical changes in recharge rates, and location of recharge and discharge areas, all of which vary between aquifers and even within the same aquifer.

1.3 Purpose of Report

In keeping with the goals of the RWP process, regional plans must consider all sources of water, especially in areas where surface water supplies are limited or susceptible to drought or where freshwater aquifers are either of limited areal extent or have been depleted. In such areas, aquifers that produce brackish groundwater may become important sources of supply if freshwater aquifers are stretched beyond their ability to satisfy all projected demands. To provide proper guidance to RWPGs that are concerned about shortages of freshwater over the 50-year planning period, the TWDB initiated this study to assess the location and availability of brackish groundwaters in Texas, and the associated costs of desalination technology and brine disposal.

This report is intended to serve as a planning resource, and was created to aid in the development of water supply strategies and preliminary cost estimates. This document is not intended to be an exhaustive resource on the subject of desalination of brackish groundwater in Texas, and it should be understood that any proposed desalination project will require site-specific research and engineering.

1.4 Organization of Report

The TWDB is providing this report to the RWPGs and other entities as a resource to help estimate brackish groundwater availability and complete preliminary feasibility assessments for any brackish groundwater strategies that may be under consideration. Therefore, the report has been arranged to simplify the identification of brackish groundwater resources in each of the sixteen TWDB planning regions. Table 1 summarizes the major and minor aquifers and other hydrogeologic units containing brackish groundwater in each region. Figure 1 illustrates the location of major aquifers in the state and Figure 2 illustrates the location of minor aquifers and other geologic units containing brackish groundwater in relation to RWPG boundaries. It should be noted that the down-dip aquifer extents shown in Figures 1 and 2 are based on TDS criteria (usually 3,000 mg/L but sometimes 5,000 mg/L) and may not indicate the areal extent of brackish groundwater resources (up to 10,000 mg/L TDS) in the aquifers. With the exception of Figures 1 and 2, the figures in this report illustrating the brackish groundwater in individual aquifers show only the outcrop of the water-bearing zone and the TDS contour lines in that unit, but do not show the TWDB-defined base of "fresh" water.

Table 1. Major and Minor Aquifers in Each Regional Water Planning Area that Contain Brackish Groundwater

Region	Major Aquifers	Minor and Other Aquifers
A – Panhandle	Ogallala Seymour	Blaine Dockum Edwards-Trinity (High Plains) Rita Blanca Whitehorse-Artesia
B – Region B	Trinity Seymour	Blaine River Alluvium Whitehorse-Artesia
C – Region C	Carrizo-Wilcox Trinity	Nacatoch Queen City Sparta Woodbine
D – Northeast Texas	Carrizo-Wilcox Trinity	Blossom Nacatoch Queen City River Alluvium Sparta Woodbine
E – Far West Texas	Edwards-Trinity (Plateau) Hueco and Mesilla Bolsons	Bone Spring-Victorio Peak Capitan Reef Igneous Marathon River Alluvium (Rio Grande) Rustler West Texas Bolsons
F – Region F	Cenozoic Pecos Alluvium Edwards-Trinity (Plateau) Ogallala Trinity	Blaine Capitan Reef Dockum Ellenburger-San Saba Hickory Lipan Marble Falls River Alluvium Rustler Whitehorse-Artesia

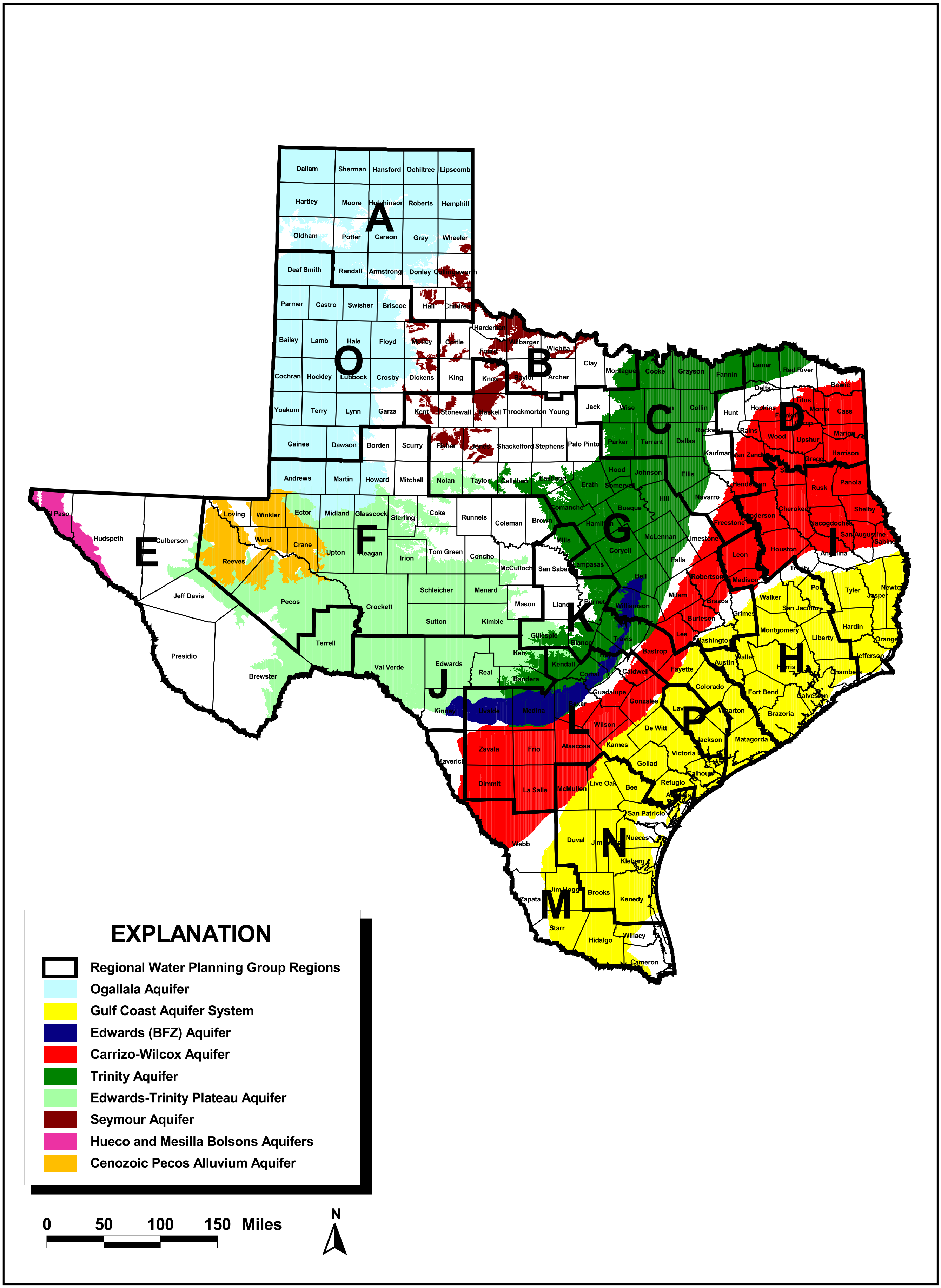
G – Brazos	Carrizo-Wilcox Edwards (BFZ) Edwards-Trinity (Plateau) Gulf Coast Seymour Trinity	Blaine River Alluvium (Brazos) Ellenburger-San Saba Hickory Marble Falls Queen City Sparta Whitehorse-Artesia Woodbine Yegua-Jackson
H – Region H	Carrizo-Wilcox Gulf Coast	Queen City Sparta Yegua-Jackson
I – East Texas	Carrizo-Wilcox Gulf Coast	Queen City Sparta Yegua-Jackson
J – Plateau	Edwards (BFZ) Edwards-Trinity (Plateau) Trinity	Ellenburger-San Saba Hickory Marble Falls River Alluvium
K – Lower Colorado	Carrizo-Wilcox Edwards (BFZ) Edwards-Trinity (Plateau) Gulf Coast Trinity	Ellenburger-San Saba Hickory Marble Falls Queen City Sparta Yegua-Jackson
L – South Central Texas	Carrizo-Wilcox Edwards (BFZ) Gulf Coast Trinity	Ellenburger-San Saba Hickory Marble Falls Queen City Sparta Yegua-Jackson
M – Rio Grande	Carrizo-Wilcox Gulf Coast	Queen City Sparta River Alluvium
N – Coastal Bend	Carrizo-Wilcox Gulf Coast	Yegua-Jackson
O – Llano Estacado	Ogallala Seymour	Dockum Edwards-Trinity (High Plains) Whitehorse-Artesia
P – Lavaca	Carrizo-Wilcox Gulf Coast	Yegua-Jackson

Chapter 2 contains a description of the study objectives, methods, and limitations. Chapter 3 contains a description of the aquifers and their associated brackish groundwater resources. The chapter is organized to include a section for each major or minor aquifer as well as other hydrogeologic units that contain significant brackish groundwater. This organization is similar to *Aquifers of Texas*, (Ashworth and Hopkins, 1995). Each aquifer section contains a map of the aquifer outcrop, symbols indicating water-quality data collected from wells, and in most cases, estimated contours of the TDS concentration. In some cases, contour lines were not included on the areal maps due to lack of or complexity of the data.

The discussion of hydrostratigraphy and brackish groundwater for each aquifer is illustrated with generalized schematic geologic cross sections to better illustrate the aquifer system and brackish groundwater resources. These cross sections can also be used to show how groundwater quality can vary with depth. Schematic cross sections were included where they were helpful in describing the general hydrogeology or water-quality variations in the aquifer. Although a location for each cross section is included on the water-quality map, it is very important to note that most of these cross sections are generalized for the purposes of this report, and should not be used to identify depths of fresh, slightly-saline, moderately-saline, and saline groundwater along the specified cross-section line. In many cases the depiction of different qualities of groundwater is not based on actual data, but has been estimated or generalized to give the reader a general understanding of the nature of water-quality changes in the subsurface.

Some aquifers cross several TWDB regional planning boundaries. Therefore, each aquifer description contains a table that summarizes the brackish groundwater resources in each region where the aquifer exists. In addition, references that cite estimated quantities for each aquifer description are annotated as footnotes (see Chapter 6). Chapter 3 also contains a table (Table 5) of estimated brackish groundwater volumes for each aquifer in each Regional Water Planning area (RWPA) and a table (Table 6) listing total estimated volumes of brackish groundwater by region.

Chapter 4 contains a summary of engineering design considerations and cost estimation methods for brackish groundwater desalination and concentrate disposal. Chapter 5 contains the conclusions of the report, including a summary of the brackish groundwater for each major and minor aquifer in each of the 16 RWPAs. Chapter 6 contains a more complete set of hydrogeologic references grouped by aquifer. Appendix A contains a glossary of terms and definitions.



TEXAS MAJOR AQUIFERS **FIGURE 1**

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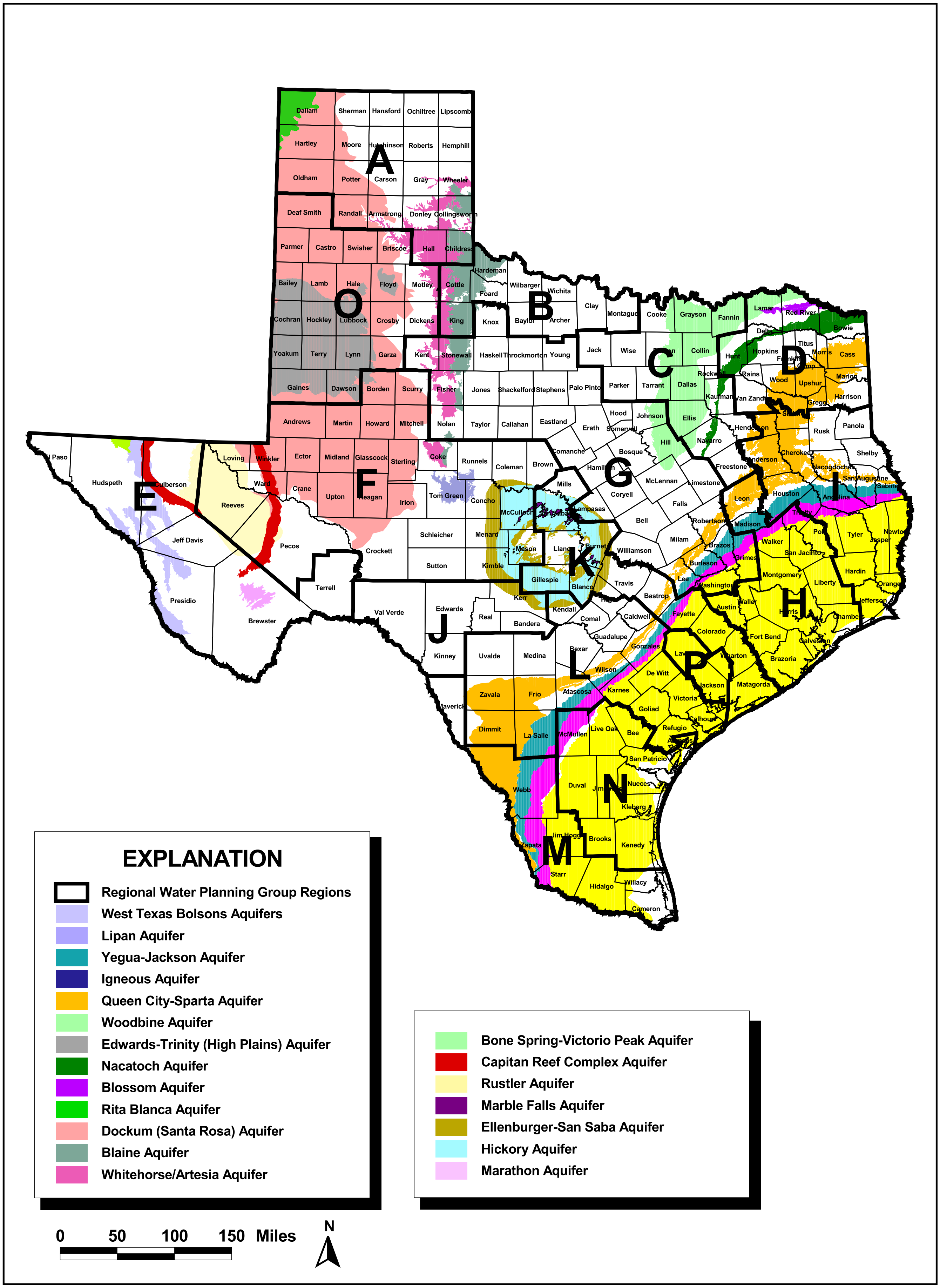

TEXAS MINOR AQUIFERS

FIGURE 2

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2.0 OBJECTIVES, METHODS, AND LIMITATIONS OF STUDY

2.1 Objectives of Study

The objective of this research is to develop a comprehensive overview of the occurrence of brackish groundwater in Texas that feasibly might be available for desalination, either now or in the future. This report focuses on the occurrence of brackish groundwater of greater than 1,000 mg/L TDS and less than 10,000 mg/L TDS and on the general production capability from aquifers containing this brackish groundwater. This quality range was selected because it represents the most economically feasible, nonfresh water to treat for water supply purposes. Because the report does not assess saline groundwater (i.e., groundwater greater than 10,000 mg/L TDS), many of the deeper saline aquifers and down-dip portions of freshwater aquifers are not considered or discussed.

This report provides a method for estimating general costs associated with brackish groundwater desalination projects. Major components included in the assessment are the cost of treatment, source water production and by-product disposal. Maps included in the report can be used to help planners identify areas where brackish groundwater may be available to meet municipal water demands or to supplement existing supplies of freshwater.

2.2 Methods of Assessment

The TWDB has identified and characterized 9 major and 21 minor aquifers in the state based on the quantity of water supplied by each aquifer. A major aquifer is generally defined as supplying large quantities of water to large areas of the state. Minor aquifers typically supply large quantities of water to small areas or relatively small quantities to large areas. These definitions are somewhat ambiguous, but have become relatively well accepted as a way to categorize aquifers in Texas. The major and minor aquifers, as presently defined, underlie approximately 81% of the state. Lesser quantities of groundwater may also be found in other parts of the state, including water-bearing units that are not officially designated as aquifers by the TWDB. Recently, the TWDB defined the Yegua-Jackson aquifer as a minor aquifer, and therefore it is included in this report. In addition to the major and minor aquifers, this report also addresses the Whitehorse-Artesia aquifer, a sand/dolomite/gypsum unit found in West-Central Texas which contains mostly brackish groundwater. Significant river alluvium systems are also discussed.

The surface extent, or outcrop, of an aquifer is the area over which the water-bearing formations are exposed at the land surface. This area corresponds to the principal recharge zone for the aquifer. Some water-bearing formations dip below the surface and are covered by other formations. Aquifers with this characteristic are common, although not exclusive, in eastern Texas and the Texas Coastal Plain east and south of Interstate Highway 35. Aquifers covered by less permeable formations, such as clay, are hydraulically “confined” and may occur under artesian pressure.

Historically, the TWDB has defined aquifer water quality in terms of TDS concentrations expressed in milligrams per liter (mg/L) and has classified water into four broad categories; fresh (less than 1,000 mg/L), slightly-saline (1,000 - 3,000 mg/L), moderately-saline (3,000 - 10,000 mg/L), and very-saline (10,000 - 35,000 mg/L) as depicted in the schematic below.

1,000 mg/L 3,000 mg/L 10,000 mg/L

Fresh	Brackish		Saline
Fresh	Slightly-saline	Moderately-saline	Very-saline

The colors used above to signify different salinities are used in all of the maps and cross sections for each of the individual aquifer descriptions in Chapter 3.

Total dissolved solids is the most commonly used parameter to describe overall groundwater quality because it is a measure of all of the dissolved constituents in water. For this report, TDS will be used as the general description of groundwater quality. The term “brackish”, as used in this report, describes slightly-saline or moderately-saline groundwater and thus includes water between 1,000 and 10,000 mg/L TDS.

Official TWDB delineations of the down-dip boundaries of such aquifers as the Edwards (BFZ), Trinity, Queen City, Sparta, and Carrizo-Wilcox have historically been based on water quality, specifically the TDS concentrations that meet the needs of the aquifers’ primary uses. The down-dip extent of most aquifers in the state is defined by the 3,000 mg/L dissolved solids level, as groundwater with less than 3,000 mg/L TDS meets most agricultural and industrial needs. However, a few aquifers have different TDS criteria defining the aquifer extent, including: Edwards (BFZ) (1,000 mg/L TDS); Dockum (5,000 mg/L TDS); Rustler (5,000 mg/L TDS); and Blaine (10,000 mg/L TDS).

The occurrence of brackish groundwater in the aquifers and RWPAs was characterized base on availability, productivity, and source water production cost. Each of these criteria was ranked as low, moderate, or high (Table 2).

Table 2. Summary of Brackish Groundwater Categories and Potential Scores

Categories	Availability	Productivity	Source Water Production Cost
Possible Scores	Low	Low	Low
	Moderate	Moderate	Moderate
	High	High	High

The availability of brackish groundwater is a general measure of the amount of brackish groundwater in a water-bearing unit. Availability was given a score of low, moderate, or high as a semi-quantitative indication of the relative abundance of brackish groundwater in a particular aquifer within each particular region. It is important to note that these terms refer to the overall availability of brackish groundwater from an aquifer, and do not necessarily fill a demand. If a demand were small, even an aquifer with a “low” availability might be a suitable source.

Productivity is a general measure of the production capacity of an aquifer. This criteria measures the ease of production from an aquifer for municipal or industrial purposes considering transmissivity of the aquifer and the production capacity of typical wells. Productivity scores are low, moderate, or high based on the estimated average productivity of a wellfield in the brackish portion of an aquifer. Table 3 summarizes the basis for the productivity scores. It is important to note that the transmissivity ranges in Table 3 are very general and broad and were used only as a general guide in characterizing productivity. The productivity ranges selected for "low", "medium", and "high" are based on small to medium-size demands. For example, a "high" productivity rating (5 MGD) is based on meeting demand of a medium-size user, but would not necessarily meet the high demands of a large user. It should also be noted that the production rates of desalinated water will be somewhat less than the rates in Table 4 because some of the water will be lost as concentrate. The percentage loss may depend on the treatment processes selected, the engineering design, and disposal methods.

Table 3. Basis for Productivity Scores

Productivity	Wellfield Potential (MGD[1])	Wellfield Potential (AFY[2])	Transmissivity Range (gal/day/ft)
Low	0 – 2	0 – 2240	<10000
Moderate	2 – 5	2240 – 5600	10000-30000
High	5+	5600+	>30000

[1]MGD = million gallons per day

[2]AFY = acre-feet per year

Source water production cost is an indication of the relative cost that would be incurred to produce the brackish groundwater, but does not consider the cost of treatment or the cost of brine disposal because each of these variables is location and project-specific. The source water production cost is scored as low, moderate or high based in a general way on the depths of wells and the water levels in an aquifer.

It should be noted that the scores in Table 3 are based on the assumption that the water will be used for municipal or industrial uses. This assumption was made because municipal and specialized industrial uses are most often the highest value demand (i.e., the cost of desalinated water can be recovered) and are, in general, the only economically feasible uses for desalinated water in Texas at this time. Under this assumption, the practicality of using brackish groundwater from very low-producing formations is relatively low because it would not be possible to retrieve the significant quantities of groundwater required by the municipal and industrial demands. On the other hand, a productivity score of "low" does not necessarily preclude the use of the brackish groundwater for domestic purposes (considering the relatively widespread use of in-house, point-of-use reverse osmosis systems) or for specialized "high-value" demands in any usage category. For example, there may be areas where there is a relative abundance of brackish groundwater, but relatively low well yields preclude the production rates required for typical municipal and industrial demands. The aquifer scores would indicate "moderate" availability, "low" productivity, and "high" overall cost because the scoring assumes typical industrial and municipal demands. But if specialized high-value uses were considered, the productivity might be higher. Examples of high-value applications include augmentation of other sources to offset seasonal periods of high demand, low-volume, high-quality commercial or industrial facilities, and low-volume communities that are located significant distances from other freshwater sources.

In addition, the nature and extent of brackish groundwater in a particular aquifer may be different in different regions for several reasons, and thus the score for the same aquifer may be different for different RWPAs. Therefore, it is important to remember the assumptions and objectives of Table 3 when comparing the scores.

2.3 Sources of Data and Information

The TWDB well database and the Texas Commission on Environmental Quality (TCEQ) public water supply database were the primary source of water-quality data for this study. Water-quality information was assimilated from 39,190 wells across the state, including domestic, irrigation, industrial, and public water supply wells. Approximately 6,340 public water supply wells were assessed for this study, but only those with water-quality information for untreated groundwater and with TDS data were used in this assessment. Table 4 summarizes the number of wells used for the assessment of each aquifer. If a well was sampled on more than one date (i.e., contained more than one TDS measurement), the most recent data were selected for inclusion in the assessment. Historical changes in TDS were not evaluated.

Table 4. Summary of Water-Quality Data for Each Aquifer from the TWDB Well Database

Aquifer	Number of Wells
Major Aquifer Systems	
Hueco and Mesilla Bolsons	598
Cenozoic Pecos Alluvium	916
Seymour	1,992
Trinity	6,199
Edwards-Trinity (Plateau)	4,797
Carrizo-Wilcox	3,641
Ogallala	5,951
Edwards (Balcones Fault Zone)	646
Gulf Coast	6,973
Minor and Other Aquifer Systems	
Dockum	896
West Texas Bolsons	250
Rustler	54
Marathon	5
Igneous	124
Capitan Reef Complex	52
Bone Spring/Victorio Peak	108
Rita Blanca	24
Edwards-Trinity (High Plains)	153
Blaine and Whitehorse-Artesia	671
River Alluvium	971
Hickory	559
Ellenburger	260
Marble Falls	20
Lipan	200
Woodbine	713

Aquifer	Number of Wells
Blossom	61
Nacatoch	209
Queen City- Sparta	1,441
Yegua-Jackson	706

In most cases, the water-quality data summarized in Table 4 were the most important source of data used for the assessments. For some aquifers, including the Carrizo-Wilcox, Queen City, Sparta, Yegua, Jackson, and Gulf Coast, electric logs and published cross sections containing electric logs showing the vertical and lateral litho-stratigraphic framework and water quality of the aquifers were also used to complete the assessments.

The electric logs used from the published cross sections (Baker, 1979 and 1995, and Dodge and Posey, 1981) are mostly induction and dual-induction logs. Log curves shown on the sections are the spontaneous potential (SP) on the left of the centerline of each well log and a resistivity curve having a shallow depth of investigation on the right side. The following rules of thumb were used to qualitatively estimate water quality from the reduced-scale logs if not shown on the sections: (a) deflection of the SP curve to the right and high resistivity indicates groundwater of less than 3,000 mg/L TDS; (b) slight SP deflection to the left or no deflection and with associated resistivity curves showing some resistivity indicates water of about 3,000 mg/L TDS; and (c) SP deflection to the left with little or no resistivity shown on the log indicates groundwater of about 10,000 mg/L TDS or greater.

2.4 Assumptions and Limitations of Study

2.4.1 Scale of Study

This statewide assessment of brackish groundwater will be helpful for planning purposes and for developing initial cost assessments, but there are several limitations that should be observed when using the report. The objectives of this study influenced the level of detail incorporated into the study and the type of results presented. This report is mainly intended to support regional water-supply planning. Therefore, the report does not typically go into detail about local-scale issues with regard to the brackish groundwater resources.

2.4.2 Availability of Data

Another issue that becomes apparent for some aquifers is the lack of water-quality data or the irregular distribution of data. As shown in Table 4, the quantity of data varies for each aquifer. Two types of data shortages generally exist. First, there may simply be a lack of water-quality data throughout an aquifer, which may be caused by a lack of wells or by a lack of water quality analyses for existing wells. This type of data sparseness is more prevalent for minor aquifers. Second, there is a general lack of water-quality data for all aquifers in areas where the TDS concentrations are greater than 3,000 mg/L. Because this type of groundwater was previously considered unusable, very few wells are drilled in these areas. This type of data sparseness generally occurs in the down-dip portions of aquifers where it is generally understood that water-quality degrades with depth. These high-TDS areas have not been developed in the past. Exploratory wells drilled in these zones that encountered high-TDS water are often plugged and abandoned without a water sample being collected for analysis. Stated succinctly, the water-quality database is probably biased toward lower TDS measurements.

In some cases, geophysical logs of deep boreholes are either scarce or non-existent in brackish sections of water-bearing units because there has been no reason to perform geophysical logging to date. In areas where oil and gas fields are present, there are typically more geophysical logs available, and more detailed assessments have been completed.

2.4.3 Data Quality

Data quality also varies because there is always some level of uncertainty in all data based on collection methods, analytical techniques, reporting discrepancies, and many other factors. The water-quality data, including TDS measurements, were collected over the last 80 years by many different people using different methods of sampling, analysis and reporting. It should also be noted that wells are sometimes screened across several productive units of an aquifer in order to maximize production. This well completion technique allows groundwater from several distinct aquifer units to be mixed in the well bore during pumping, causing water quality of the sample to be averaged for the screened interval. Based on the data available for each well, there is no practicable way to decipher which wells are screened across multiple zones and if they are, how that completion affects water-quality measurements. If some wells were completed differently, it is conceivable that wells exhibiting brackish groundwater TDS concentrations could produce fresh water from some zones and even higher TDS water from other zones.

2.4.4 Natural Variability of Water Quality

Groundwater quality can vary significantly in the same aquifer for many reasons including mineral composition of the aquifer material, geochemical processes, groundwater flow velocity, residence time, long-term historical changes in recharge rates, and location of recharge and discharge areas. Even if there is relatively dense coverage of water-quality data across an aquifer, it is apparent from the existing data in some aquifers that the local variability of the water quality is significant and that the data may not be sufficient to describe water-quality trends or anomalies. The figures presented in this report illustrate 1,000, 3,000, and 10,000 mg/L TDS contour lines if there are sufficient data to support such interpolation. However, it is sometimes impractical to interpolate contour lines in areas that exhibit significant spatial variability. For this reason, all of the data from the wells were posted on the maps so the reader could assess what data were available and how they were used to interpolate contour lines. Contours of water quality should only be considered as indicators of general trends and should not be assumed to represent local-scale variability.

2.4.5 Volume Calculations

The volume of brackish groundwater was estimated for each aquifer in each RWPA. These estimates were based on generalized aquifer characteristics in each region and are not intended to be used as precise availability values. They are included in this report to provide a means of evaluating whether a brackish groundwater desalination strategy is feasible in an RWPA and whether or not it should be investigated further.

The volume of brackish groundwater in each aquifer within a RWPA was estimated by first determining the areal extent of groundwater containing 1,000-3,000 mg/L TDS and 3,000-10,000 mg/L TDS on the areal maps of each aquifer. An average aquifer thickness and storage coefficient were also estimated for each of these areas. Different assumptions were used to estimate brackish groundwater volumes in confined and unconfined portions of the aquifers. In confined sections, the amount of brackish groundwater that could be developed from aquifer storage was calculated by assuming that the water levels would be decreased a specified amount over the entire aquifer area. This estimate does not account for any potential recharge from precipitation or from inflow of brackish groundwater laterally or vertically. In most confined aquifer sections, this assumption underestimates the volume of water that would be available for development and is considered a conservative, or low estimate. In addition to this conservative estimate, another estimate was developed to represent the high range of potential brackish groundwater volume. The high volume estimate was determined by calculating the actual volume of brackish groundwater in the voids of the aquifer material. This volume is considered a high estimate because it is unlikely that the entire section of a confined aquifer would be dewatered. The more likely value would fall somewhere between the low and high estimates because that represents situations that currently exist in the confined sections of the Carrizo-Wilcox and Gulf Coast aquifers which produce significant quantities of groundwater. Specifically, water levels decline with increased production, but then due to recharge from precipitation and lateral and vertical inflow of groundwater, water levels stabilize at a lower level. Although the estimates contained in this report are basic, they do provide a preliminary assessment of the brackish groundwater resources in each RWPA. The estimated volumes of brackish groundwater in each aquifer by RWPA are summarized in Table 5 at the end of Chapter 3.

In some aquifers, the water-quality data showed significant variability and did not contain trends that could be contoured but rather a mixture of brackish water within the fresh water. This may be due to natural variability in water quality. In these cases, the areal extent of groundwater containing 1,000-3,000 and 3,000-10,000 mg/L TDS was not determined by calculating the area between the contour lines on the maps. Instead, the respective areas were calculated by estimating the total area of the mixed water quality and then apportioning the areas that would fall into the 1,000-3,000 and 3,000-10,000 mg/L TDS ranges based on the percentage of observed data in those ranges.

To estimate the volume of brackish groundwater, storage coefficients were estimated for each aquifer in each RWPA. The estimates of the hydraulic properties at this scale were based on published data and professional judgment but are still very generalized estimates and may not represent site-specific conditions. When developing site-specific feasibility studies, users are encouraged to refer to the more detailed hydrogeologic reports for each aquifer referenced in Chapter 6 to obtain localized information. In addition, it may be necessary to collect site-specific data to confirm aquifer characteristics and brackish ground water quality.

3.0 AQUIFER SYSTEMS

3.1 Major Aquifer Systems

3.1.1 Hueco and Mesilla Bolsons

The Hueco and Mesilla Bolsons aquifers are located in far West Texas in El Paso and Hudspeth Counties, as shown in Figure 3. Both of these aquifers are Quaternary to Tertiary age basin-fill type aquifers, and are separated by the Franklin Mountains in Texas. A generic cross section of these aquifers through the El Paso metropolitan area is shown in Figure 4. These aquifers are used extensively in the region for municipal water supply purposes by the City of El Paso and other smaller entities.

Groundwater in the Hueco and Mesilla Bolsons aquifers is typically found under water-table conditions. Wells completed into these aquifers are capable of producing up to 1,000 gpm. Aquifer tests indicate that transmissivities range from 50,000 to 300,000 gpd/ft, with specific yield estimates of 0.15 to 0.20, and specific capacities as high as 200 gpm/ft.

Recharge to the Hueco and Mesilla Bolsons is from precipitation runoff from the Organ and Franklin Mountains, principally occurring at the margins of these basins. Additional recharge occurs through the infiltration of water from the Rio Grande and from irrigation canals and drains. Much of the water in the Rio Grande is recirculated irrigation water, and therefore fairly high in total dissolved solids. Historically, discharge from these aquifers was by evaporation and to seeps into the Rio Grande Alluvium; today, most discharge is to wells.

The chemical quality of the Hueco and Mesilla Bolsons is quite variable. In general, a wedge of fresh water is located in the upper portions of the aquifer that is thickest against the Franklin Mountains. This wedge of fresh water is completely surrounded by poorer quality water and the fresh water lens thins farther from the mountains.

A detailed description of each aquifer is given below.

Hueco Bolson- The Hueco Bolson is the larger of the two aquifers within Texas. The Hueco Bolson extends down the Rio Grande in El Paso County well into Hudspeth County, as shown in Figure 4, where it thins significantly and is not nearly as productive as it is in the El Paso metropolitan area. The Hueco Bolson consists of up to 9,000 feet of unconsolidated basin fill in the El Paso area, composed mainly of sand, silt, gravel, and caliche in the upper zone, and clay and silt in the lower zone. To the southeast, the aquifer is only 1,000 to 3,000 feet thick. Sediments in the southeast region are mostly fine-grained, and coarse-grained sediments are found only in the upper 200 to 400 feet.

Most of the groundwater production in the region is from the Hueco Bolson, with most being used for municipal supply purposes and occurring in the El Paso metropolitan area. The City of El Paso has produced a significant amount of water from the Hueco Bolson, which has resulted in lowered water levels as well as the overall reduced quality (increased TDS) of the groundwater being produced. Ciudad Juarez, located on the

Mexican side of the international border, uses significant quantities of water from the Hueco Bolson aquifer, which exacerbates the problems of declining water levels and deteriorating water quality. Water level declines are greatest in the El Paso metropolitan area, with rates of decline of up to five feet per year occurring in some areas.

The southeast portion of the Hueco Bolson contains increased amounts of gypsum, and recharge from the Diablo Plateau and the Malone/Finley Mountains is limited. Therefore, much of the Hueco Bolson in this area contains groundwater with 1,000 to 5,000 mg/L TDS in the shallower zones, and more than 5,000 mg/L TDS in deeper zones. Many test wells put into the Hueco Bolson in the southeastern section of the aquifer encountered no fresh water at all.

Mesilla Bolson- The Mesilla Bolson is located on the west side of the Franklin Mountains as shown in Figure 4. Only a small portion of this aquifer is located within Texas, and much larger sections are found north and west into New Mexico and south into Mexico. The Mesilla Bolson is much thinner within Texas than the Hueco Bolson, containing up to 2,000 feet of clay, silt, sand, and gravel.

The Mesilla Bolson contains three wedges of fresh water which are found in three producing horizons, typically called the shallow, intermediate, and deep zones. Each of these fresh water zones is surrounded by brackish water. In the Mesilla Bolson, the freshest water is found in the deepest zone, with progressively higher salinity water being found in shallower zones. The shallowest zone is hydrologically connected to the overlying Rio Grande alluvium. In general, salinity in the Mesilla Bolson increases from north to south. However, the salinity varies inconsistently both vertically and laterally across the valley.

Groundwater in the Mesilla Bolson generally flows to the south with a hydraulic gradient of four to six feet per mile. Water levels in the center of the Mesilla Valley are generally between 10 and 25 feet below land surface. Water level declines are less severe in the Mesilla aquifer than in the Hueco Bolson.

Summary

Much of the Hueco Bolson outside of the area along the Franklin Mountains contains brackish water. It has been estimated that approximately 10 million acre-feet of fresh water remains in storage in the Hueco Bolson in the El Paso area alone, most in the El Paso metropolitan area[1]. It has also been estimated that more than 3 million acre-feet of slightly-saline water (1,000 to 3,000 mg/L) is present beneath and adjacent to the Hueco Bolson in the El Paso area[1]. Many of the areas with brackish water, however, may not be as highly transmissive, and therefore overall productivity may be limited in some areas. Previous investigations and an analysis of existing data indicate that large quantities of slightly-saline groundwater are available from the Mesilla Bolson, including a significant amount within Texas.

<u>Availability</u>- HIGH- It is difficult to estimate an exact amount of recoverable brackish water from aquifers like the Hueco and Mesilla Bolsons, which are thousands of feet thick and which have little data available for much of the brackish sections. However, because these aquifers are as extensive as they are, and because they contain thousands of feet of brackish water, the availability of brackish water from these aquifer

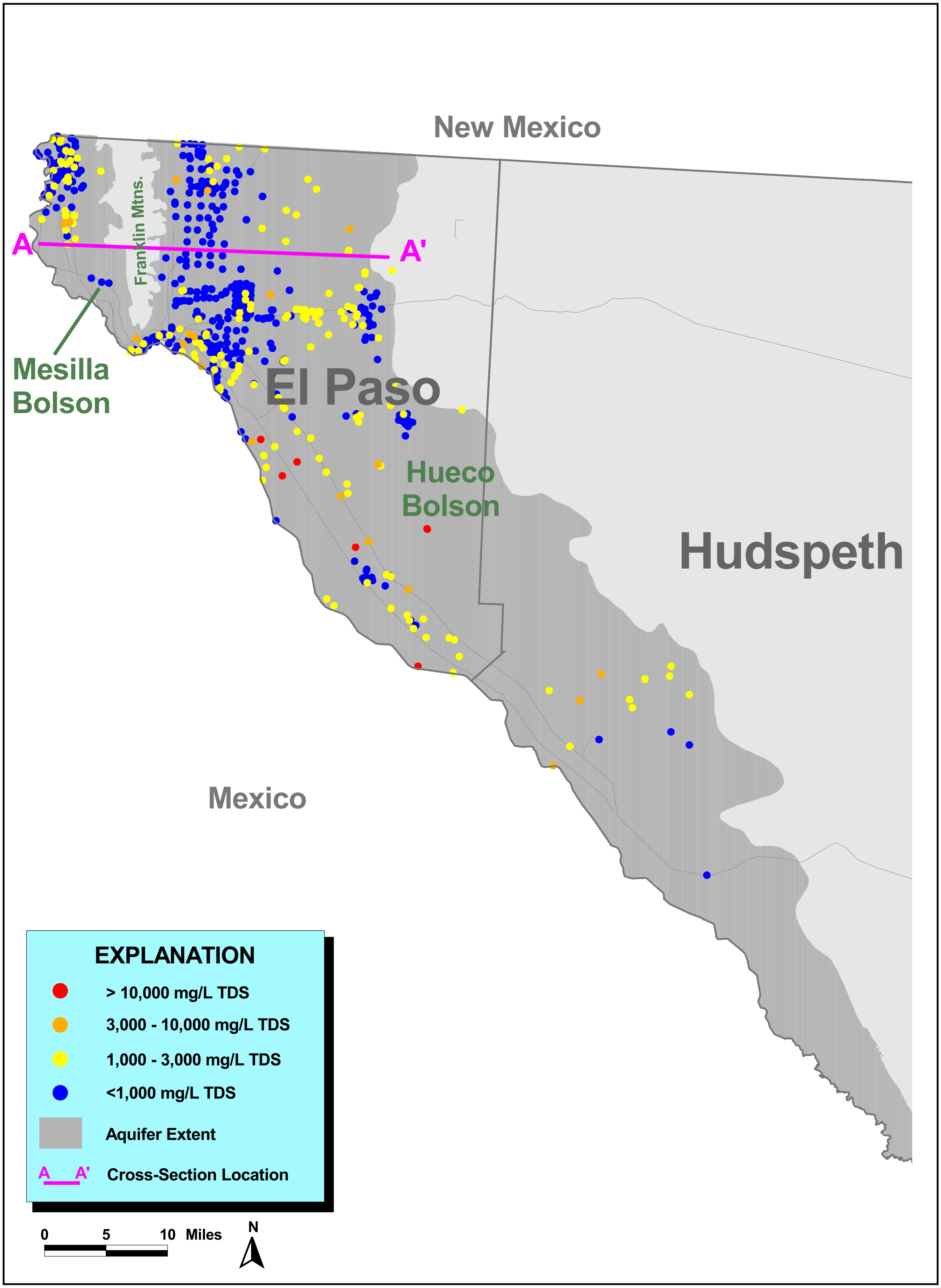
must be considered high. The City of El Paso and Fort Bliss are currently evaluating brackish-water availability as part of their desalination project.

Productivity- MODERATE- Although fresh groundwater from both the Hueco and Mesilla Bolsons aquifers is fairly easily produced, these aquifers tend to be tighter and less transmissive where the brackish groundwater is found, which reduces the potential productivity.

Source Water Production Cost- LOW to MODERATE- Because the formations containing brackish water may be less productive, and water levels may be deep, production costs are expected to be moderate. As brackish groundwater is depleted, water levels will continue to drop and production costs would be expected to increase. Production costs in the Mesilla Bolson may be somewhat lower than in the Hueco Bolson because the poorer quality groundwater is found at shallower depths.

Summary of Brackish Water In the Hueco Bolson Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
E- Far West Texas	High	Moderate	Moderate

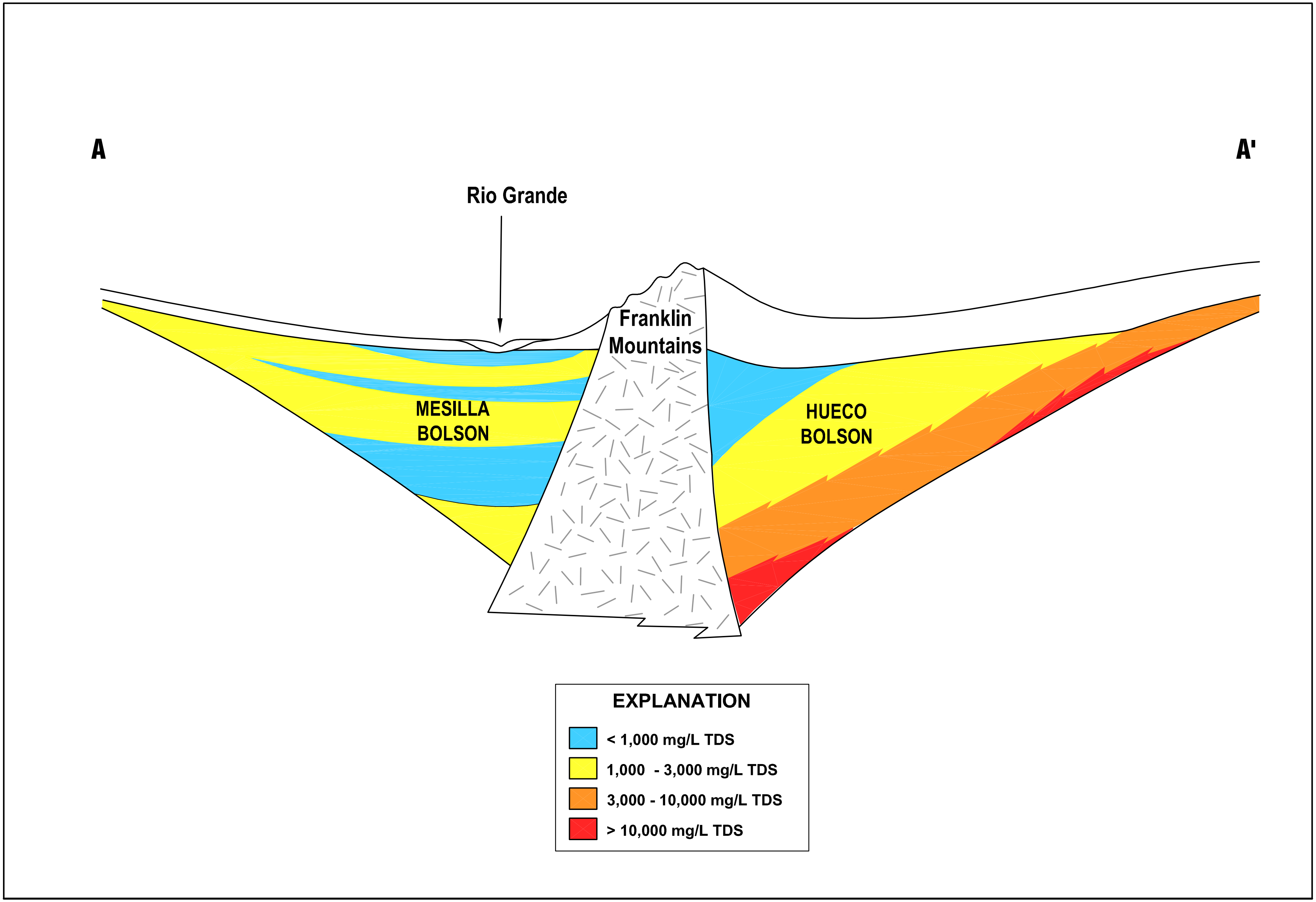
Summary of Brackish Water In the Mesilla Bolson Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
E- Far West Texas	High	Moderate	Low to Moderate



GROUNDWATER QUALITY IN THE HUECO AND MESILLA BOLSONS AQUIFERS

FIGURE 3

LBG-GUYTON ASSOCIATES



SIMPLIFIED CROSS SECTION OF THE HUECO AND MESILLA BOLSONS AQUIFERS WITH GENERALIZED WATER QUALITY RANGES **FIGURE 4**

(Modified from Ashworth and Hopkins, 1995)

LBG-GUYTON ASSOCIATES

3.1.2 Cenozoic Pecos Alluvium

The Cenozoic Pecos Alluvium is a Quaternary to Tertiary age basin-fill aquifer located in West Texas in Crane, Loving, Pecos, Reeves, Ward, and Winkler Counties, as shown in Figure 5. The aquifer is composed of two hydrologically separate sediment-filled troughs called the Pecos Trough to the west and the Monument Draw Trough to the east. Most of the groundwater produced in the Pecos Trough is used for irrigation, while most production in the Monument Draw Trough is exported to cities east of the aquifer area.

A cross section of the Cenozoic Pecos Alluvium aquifer is shown in Figure 6. The aquifer consists of up to 1,500 feet of alluvial fill consisting of unconsolidated sand, silt, clay, gravels, and caliche. The alluvial fill unconformably overlies, and is hydrologically connected to, several underlying aquifers, including the Edwards-Trinity (Plateau), the Dockum, and the Rustler.

Groundwater in the Cenozoic Pecos Alluvium occurs under unconfined or semi-confined conditions, although artesian conditions may be encountered in certain areas. Groundwater tends to flow toward the Pecos River in each of the two troughs, and there appears to be very little flow between the two troughs. The depth to groundwater is usually less than 50 feet, however, in heavily irrigated areas, depths to groundwater of up to 300 feet have been observed. Wells completed in this aquifer can produce up to 2,000 gpm, with specific capacities of greater than 100 gpm/ft. Transmissivities in the aquifer average about 40,000 gpd/ft, but may be as high as 150,000 gpd/ft in the thicker sections. Specific yields from the aquifer are estimated to be about 0.12.

Recharge to the aquifer occurs through the infiltration of precipitation, especially over sand dunes located over the Monument Draw Trough, as well as by the infiltration of water from canals and irrigation return flow. Some additional recharge occurs by inter-aquifer leakage from the south and west from the Rustler and Edwards-Trinity (Plateau). Discharge is through base flow to the Pecos River, to vapotranspiration (especially close to the Pecos River), and to wells producing from the aquifer.

Water quality in the Cenozoic Pecos Alluvium aquifer is highly variable due to natural conditions as well as some man-made sources. Water quality in the Monument Draw Trough tends to be better than groundwater in the Pecos Trough, varying from fresh to moderately-saline, while Pecos Trough groundwater varies from slightly- to moderately-saline. Figure 5 shows the location of areas with slightly- and moderately-saline groundwater. As shown in this figure, significant portions of both sections of the aquifer contain poorer quality water. However, specific areas of a certain type or quality of water cannot be identified because the water quality varies so significantly across the area, both vertically and laterally.

In general, water quality in the Cenozoic Pecos Alluvium becomes poorer with increasing depth, although groundwater quality in the very shallowest portions of the Pecos Trough aquifer (less than 100 feet) appears to be the poorest. Evapotranspiration and the seepage of irrigation return flow may have caused an increase in TDS in shallow groundwater. In addition, the past surface disposal of oil-field brines has caused an increase in TDS in shallow groundwater, especially in the Monument Draw Trough. It has been estimated that up to twenty percent of water applied for irrigation reaches the water table as recharge[1]. Irrigation water significantly increases TDS in shallow groundwater because constituents are concentrated in the water due to evapotranspiration and the water has the opportunity to leach minerals from the soil profile as it passes downward.

Summary

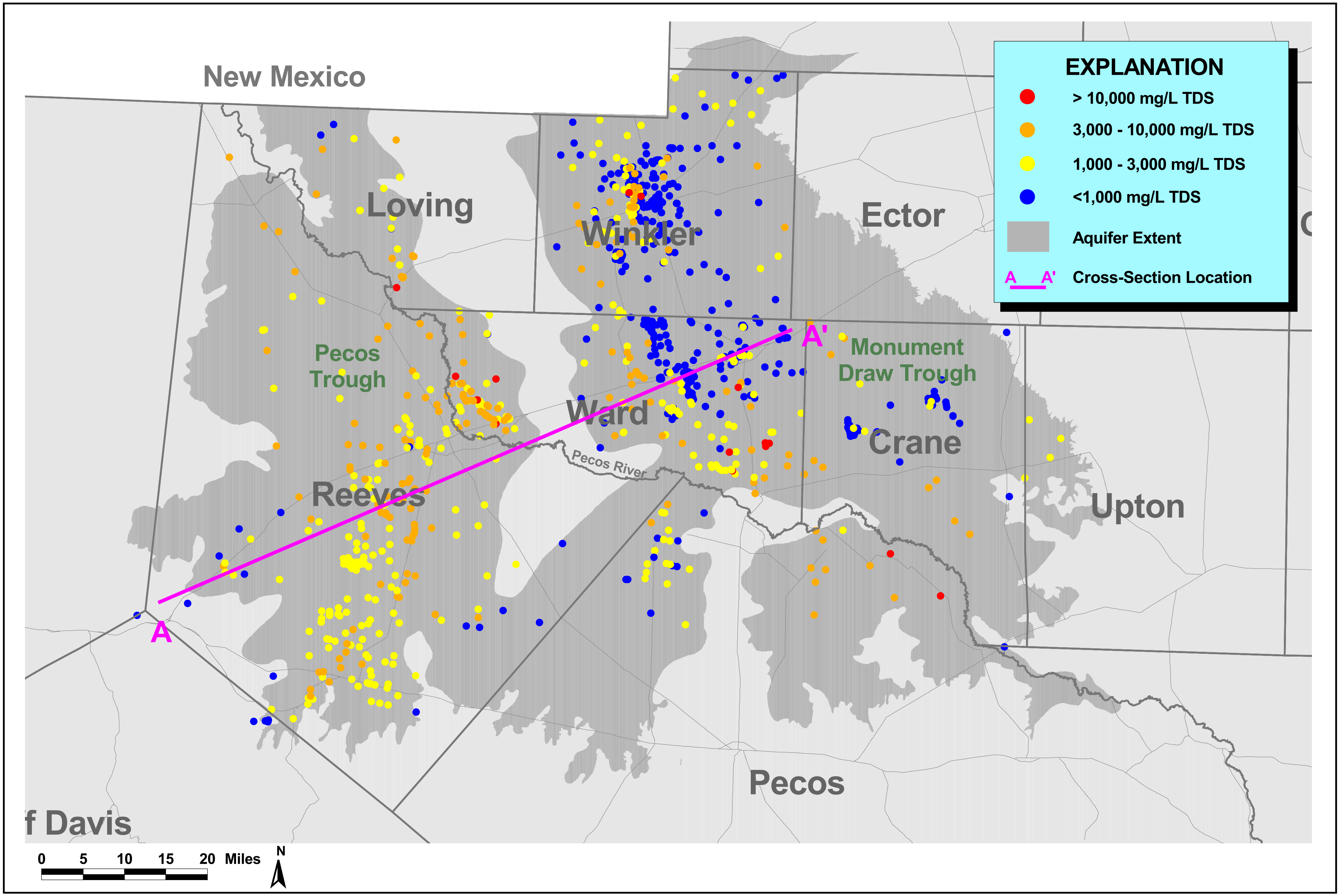
A significant amount of slightly- to moderately-saline water is available from the Cenozoic Pecos Alluvium aquifer from both the Monument Draw Trough and the Pecos Trough. Estimates of up to tens of millions acre-feet of water is available in storage from this aquifer, much of which is between 1,000 mg/L and 10,000 mg/L in total dissolved solids[1]. The aquifer is capable of yielding large quantities of water, and so should be considered a good candidate for the production and use of brackish water. Most groundwater in Pecos County appears to be brackish, and desalination may be the only option in developing this water. In Winkler and Ward Counties, there are extensive reserves of fresh groundwater available. Large-scale development in this area probably should focus on the fresh water reserves before evaluating the potential for brackish water use.

Availability- HIGH- The Cenozoic Pecos Alluvium aquifer contains significant volumes of brackish groundwater, especially in the Pecos Trough. Previous estimates have put the groundwater reserves in this aquifer at tens of millions of acre-feet, much of which will be brackish in quality.

Productivity- HIGH- Where available, the productivity of brackish sections of the Cenozoic Pecos Alluvium should be good. Wells will be relatively easy to install and fairly productive.

Source Water Production Cost- MODERATE- Moderate well depths and a fairly productive aquifer result in only moderate costs to produce brackish groundwater from the Cenozoic Pecos Alluvium aquifer.

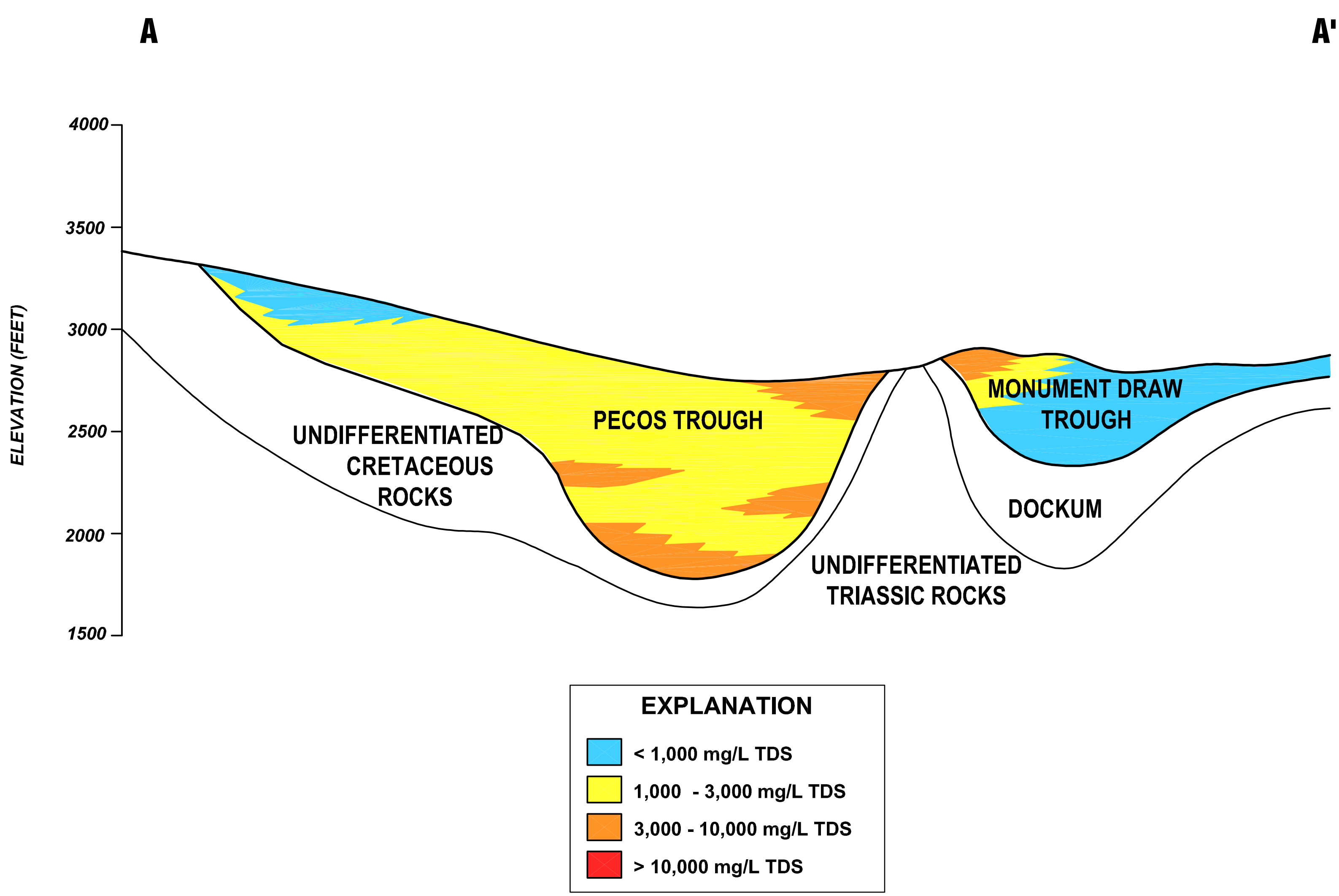
Summary of Brackish Water In the Cenozoic Pecos Alluvium Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
F- Region F	High	High	Moderate



GROUNDWATER QUALITY IN THE
CENOZOIC PECOS ALLUVIUM AQUIFER

FIGURE 5

LBG-GUYTON ASSOCIATES



SIMPLIFIED CROSS SECTION OF THE CENOZOIC PECOS ALLUVIUM AQUIFER WITH GENERALIZED WATER QUALITY RANGES

(Modified from Ashworth, 1990)

FIGURE 6

LBG-GUYTON ASSOCIATES

3.1.3 Ogallala

The Ogallala aquifer extends across the Great Plains of the central United States, from Texas to South Dakota. The southern portion of the Ogallala aquifer is found in 46 counties in the Texas High Plains, as shown in Figure 7. The Canadian River, which has eroded through the base of the Ogallala, divides the aquifer in Texas into two parts – the Northern and Southern High Plains. The Ogallala has been used extensively for more than 50 years, with nearly all of the water produced from the Ogallala being used for irrigation purposes. However, the Ogallala is also the major or sole source of water for a number of municipalities in the region.

The Ogallala aquifer is composed of Tertiary age sand, gravel, silt, and clay. These sediments have a maximum thickness of about 900 feet but are thinner in most places. Aquifers underlying the Ogallala include the Blaine and Whitehorse-Artesia aquifers, the Dockum aquifer, and various units associated with the Edwards-Trinity High Plains and Plateau aquifers. A schematic cross section of the Ogallala is shown in Figure 8.

Groundwater in the Ogallala is found under water-table conditions. Movement of groundwater in the Northern High Plains portion of the aquifer is primarily to the east, although this varies locally. In the Southern High Plains, flow is predominantly to the east-southeast – towards the eastern escarpment. The maximum saturated thickness is about 600 feet, although the average saturated thickness is less than 100 feet. Specific yields range from 0.04 to 0.22, averaging between 0.16 and 0.18. Transmissivities range from less than 500 gpd/ft to greater than 200,000 gpd/ft. Transmissivities tend to be greater than 5,000 gpd/ft, and average over 30,000 gpd/ft. The average well yield in the Ogallala is about 500 gpm, although wells with yields of more than 2,000 gpm can be found in some areas.

Recharge to the Ogallala aquifer is predominantly due to the infiltration of precipitation. Even though precipitation is limited and evaporation rates are high, the Ogallala surface soils are permeable enough that significant recharge does occur. Additionally, some recharge occurs by upward movement of groundwater from underlying aquifers. Pumping represents the greatest amount of discharge from the aquifer, with historic water-level declines in some sections of the Ogallala exceeding 100 feet.

Groundwater in the Ogallala is typically very hard. Nearly all wells in the Northern High Plains and the northern half of the Southern High Plains produce fresh water, as shown in Figure 7. In the southern half of the Southern High Plains there is a significant shift in the water quality, due in part to the upward migration of poorer quality groundwater from underlying aquifers. This tends to occur in those areas of the aquifer that are thinner and less permeable. Locally, the presence of saline lakes also affects Ogallala water quality detrimentally. Water-quality constituents that contribute to high TDS include chloride, sulfate, and fluoride.

Summary

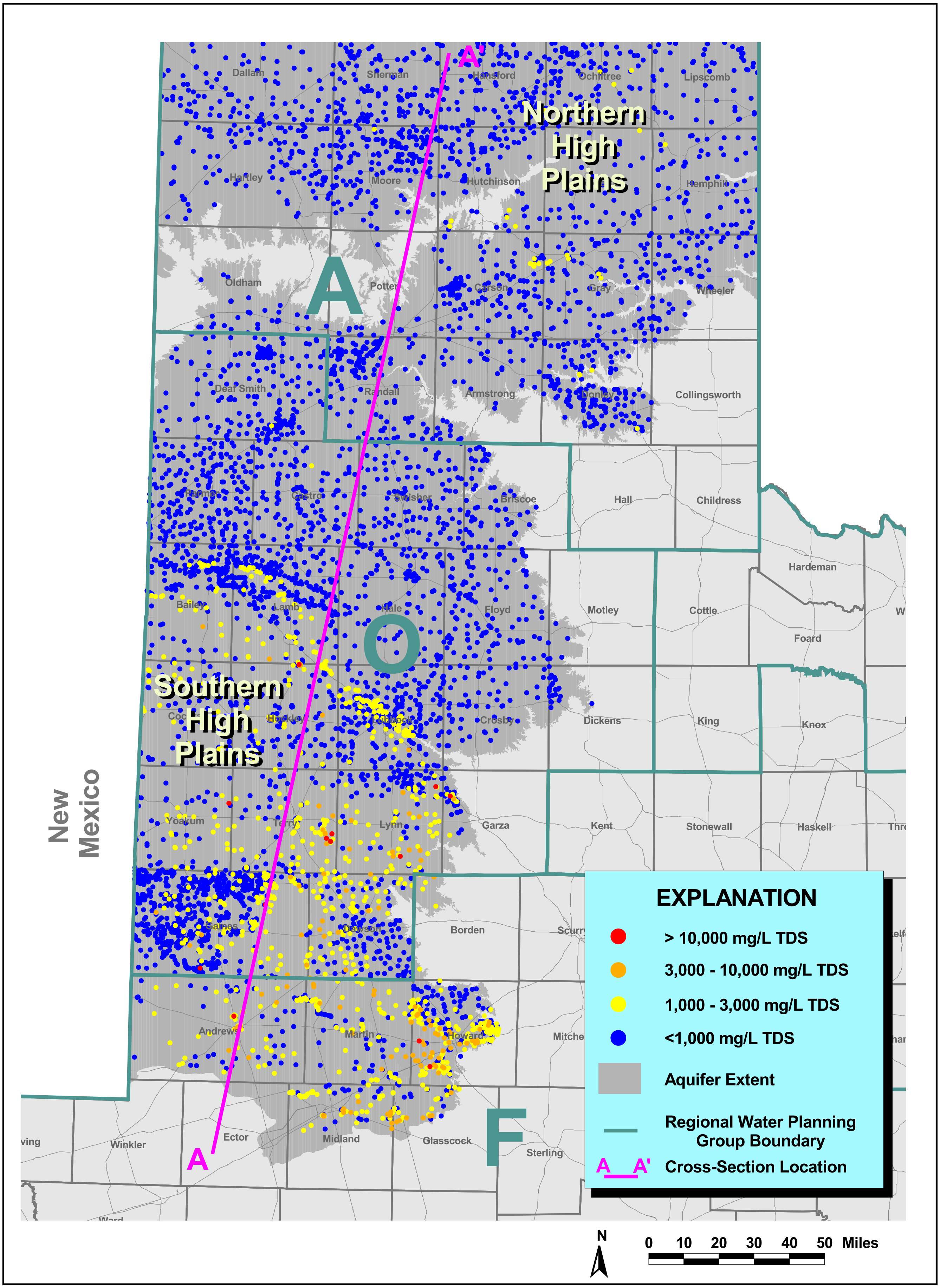
In general, most of the Ogallala in the Northern High Plains and the northern part of the Southern High Plains contains fresh groundwater. However, the southern portion of the Southern High Plains Ogallala contains some brackish groundwater. Because of the shallow and highly transmissive nature of the Ogallala, where brackish groundwater can be found, the aquifer should be considered a good brackish-water source.

Availability- LOW to HIGH. Availability is low in the Northern High Plains and northern half of the Southern High Plains, where little brackish water is found. In the southern portion of the Southern High Plains brackish groundwater is plentiful. However, in these areas, including in Region F, the Ogallala thins and the saturated section from which to produce is significantly less than most of the rest of the aquifer.

Productivity- HIGH- Where brackish groundwater is present, the productivity of the Ogallala aquifer is generally very good. However, where much of the brackish groundwater is found is where the Ogallala is thin, meaning that very large capacity production wells that are present in other parts of the aquifer may not be feasible.

Source Water Production Cost- LOW to MODERATE- Typically, well costs in the Ogallala are relatively low, the aquifer is very productive and relatively shallow. However, due to the thinner nature in the brackish sections of the Ogallala aquifer, more wells will be required to produce a required rate of water than in a typical Ogallala well field. This will tend to cause the overall costs to be more moderate.

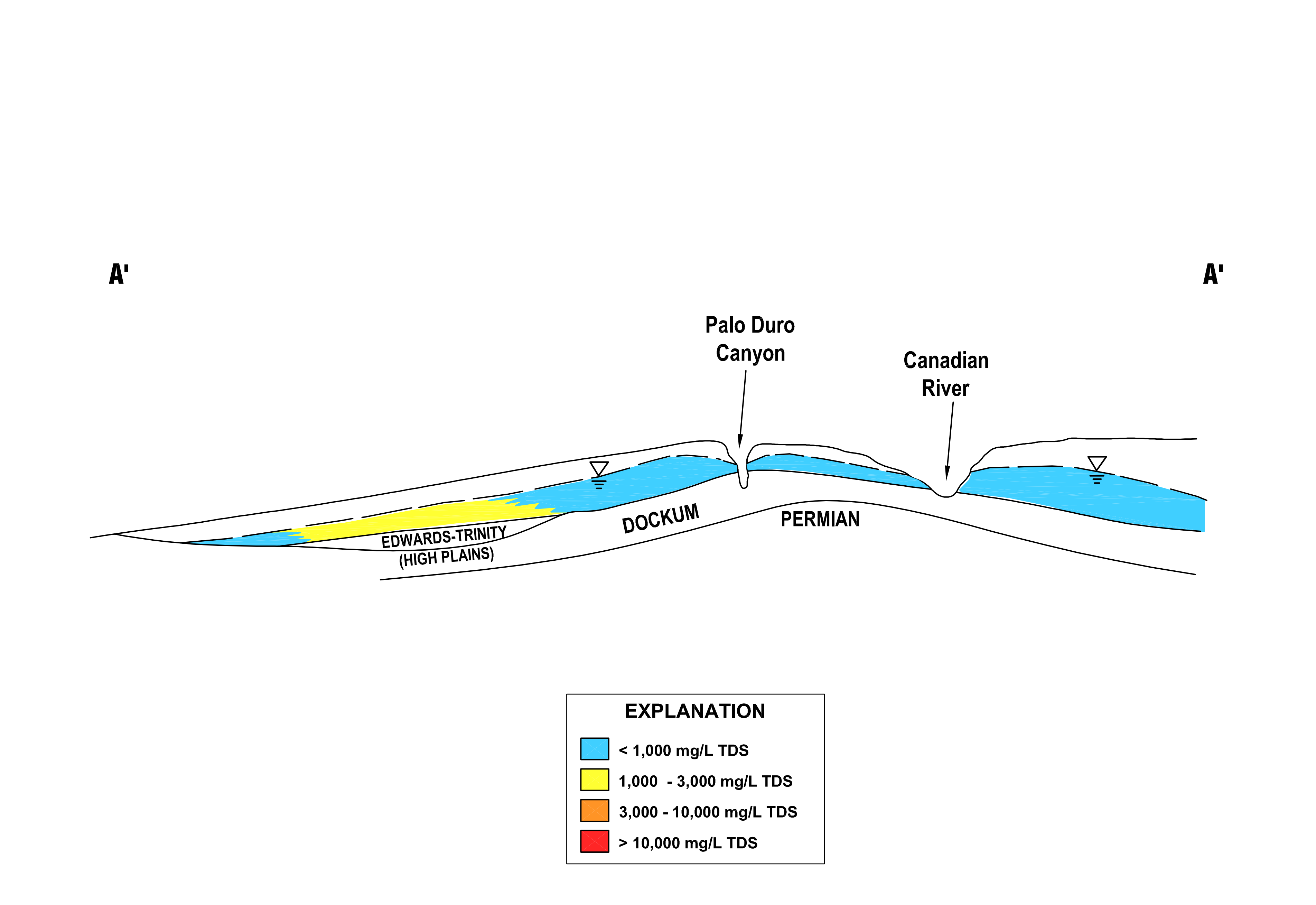
Summary of Brackish Water In the Ogallala Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
A- Panhandle	Low	High	Low to Moderate
F- Region F	Moderate	High	Low to Moderate
O- Llano Estacado	High	High	Low to Moderate



GROUNDWATER QUALITY IN THE OGALLALA AQUIFER

FIGURE 7

LBG-GUYTON ASSOCIATES



SIMPLIFIED CROSS SECTION OF THE OGALLALA AQUIFER WITH GENERALIZED WATER QUALITY RANGES

(Modified from Ashworth and Hopkins, 1995)

FIGURE 8

LBG-GUYTON ASSOCIATES

3.1.4 Seymour

The Seymour is a discontinuous, Quaternary-age alluvial aquifer scattered across 23 counties in the Panhandle and north-central Texas, as shown in Figure 9. Most of the groundwater currently produced from the Seymour is used for irrigation purposes, with less than ten percent being used for municipal supplies. The cities of Vernon, Burkburnett, and Electra are the largest municipal users of Seymour groundwater.

A schematic cross section of the Seymour is shown in Figure 10. The Seymour is composed of unconsolidated conglomerates, gravels, sands, and silty clays, which were eroded from the High Plains and deposited in discontinuous alluvial lenses. The average thickness of these sediments is typically less than 100 feet, with a maximum thickness of 360 feet occurring in northern portions of the aquifer.

Groundwater is present in the Seymour aquifer mainly under water-table conditions. Pumping tests indicate average transmissivities range from 25,000 gpd/ft to as much as 300,000 gpd/ft. Specific yields range from 0.10 to 0.20, averaging about 0.15. As might be expected, well yields vary widely, ranging anywhere from 100 to over 1,000 gpm, but average about 300 gpm.

Recharge to the aquifer is predominantly from the infiltration of precipitation, with greater recharge occurring in areas with greater sand content. Annual effective recharge has been estimated by the State to be greater than 200,000 acre-feet. Groundwater flows from these areas of recharge to lower elevations, discharging in seeps and springs and to streams and rivers in the region. The rate of groundwater movement in the Seymour has been estimated to be between 800 and 1,200 feet per year in Haskell and Knox counties[1]. In addition to seeps, springs, and evapotranspiration, a significant amount of discharge from the Seymour is from pumpage.

Groundwater quality of Seymour aquifer water tends to be fresh to slightly-saline, as shown in Figure 9. The majority of wells produce fresh water, however, local pockets of brackish groundwater are present. Higher TDS groundwater tends to be found where groundwater pumpage is high, or where other sources of contamination, such as nitrate contamination, contamination from oil-field activities, or natural salt contamination, are present. As shown in Figure 9, a higher number of wells producing slightly-saline groundwater are found in the southern portions of the Seymour, in particular in Jones County. In other sections of the aquifer, there are certain areas where some wells produce brackish groundwater, however, as shown in Figure 9, these appear to be randomly located. In addition, there are several areas of the Seymour for which there is very limited well data. In some cases, especially in the western parts of the mapped aquifer, the saturated thickness of the aquifer is very thin, and therefore is not used. The limited thickness of the aquifer in some areas also precludes their availability as a brackish water resource.

Summary

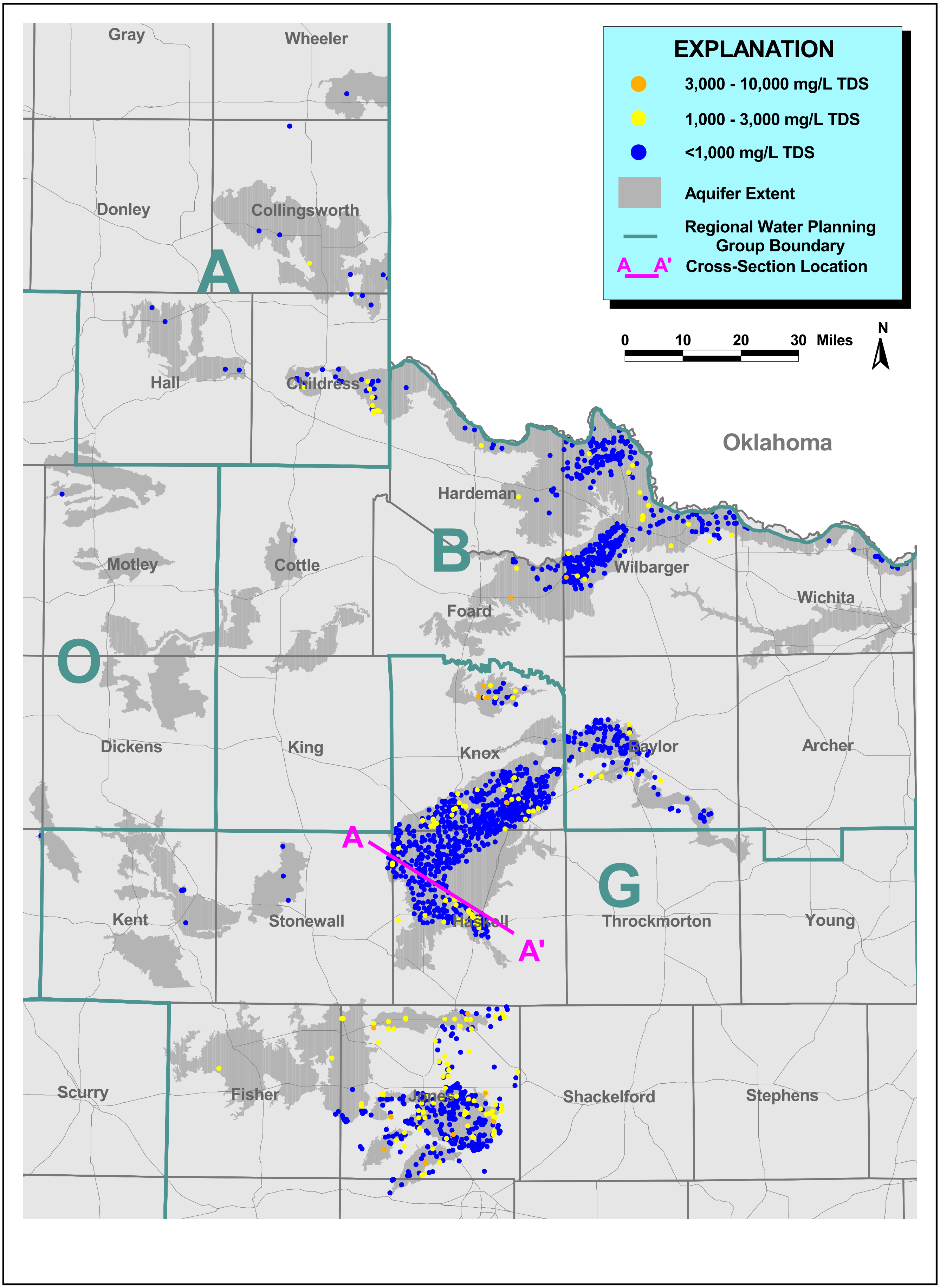
Some areas of the Seymour aquifer contain brackish groundwater, but overall, the availability of brackish groundwater is spotty or localized. In those areas where brackish groundwater is present, specifically areas in Knox, Haskell and Jones Counties, Seymour groundwater may be practical to use as a brackish water resource.

Availability- LOW to MODERATE- In general, the availability of brackish groundwater from the Seymour is low. In some areas, particularly in the southern portions of the aquifer, more brackish groundwater is available.

Productivity- MODERATE- Where brackish groundwater is available, the productivity of the Seymour is variable. This is mainly due to the variable nature of the Seymour. In places, the aquifer is very thin, and the production of large quantities of groundwater is not possible. However, in other areas, the Seymour is thicker and more productive.

Source Water Production Cost- LOW - If available and practicable, brackish groundwater will generally be relatively inexpensive to produce. Well depths in the Seymour will be shallow, and wells may be highly productive.

Summary of Brackish Water In the Seymour Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
A- Panhandle	Low	Moderate	Low
B- Region B	Moderate	Moderate	Low
G- Brazos	Moderate	Moderate	Low
O- Llano Estacado	Unknown	Unknown	Unknown



GROUNDWATER QUALITY
IN THE SEYMOUR AQUIFER

FIGURE 9

LBG-GUYTON ASSOCIATES

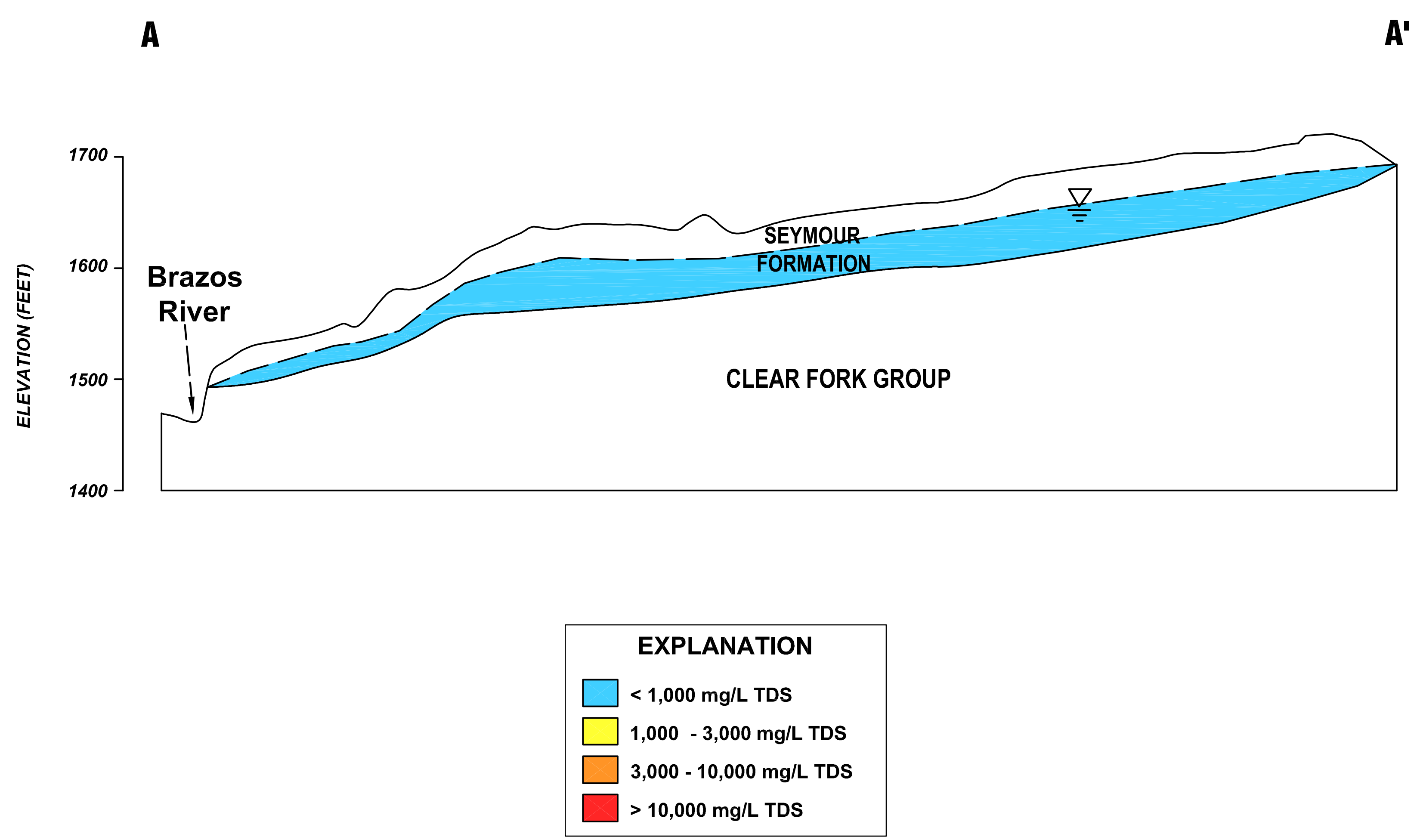


FIGURE 10

SIMPLIFIED CROSS SECTION OF THE SEYMOUR AQUIFER
WITH GENERALIZED WATER QUALITY RANGES
(Modified from Harden, 1978)

LBG-GUYTON ASSOCIATES

3.1.5 Edwards-Trinity (Plateau)

The Edwards-Trinity (Plateau) aquifer consists of Cretaceous-age limestones, sandstones, and dolomites, located from the Trans Pecos region in West Texas into North and Central Texas, as shown in Figure 11. Although in other parts of the state the Edwards and associated limestones and the formations of the Trinity Group are considered to be individual aquifers, in the Edwards and Stockton Plateau areas these formations are grouped as a single aquifer. Most of the groundwater produced from this aquifer is used for irrigation purposes. However, the aquifer is also used for domestic and stock purposes, and several municipalities, including Fort Stockton and Odessa, use groundwater from the Edwards-Trinity (Plateau) aquifer for municipal water supplies.

The Edwards-Trinity (Plateau) aquifer is comprised of the lower Cretaceous Trinity Group sediments and the limestones and dolomites of the Edwards, Comanche Peak, and Georgetown Formations[1]. These strata are relatively flat lying, and located atop relatively impermeable pre-Cretaceous rocks. Groundwater in the Edwards and associated limestones occurs primarily in solution cavities that have developed along faults, fractures, and joints in the limestone. These formations are the main water-producing units in about two-thirds of the aquifer extent. The water-bearing units of the Trinity Group are used primarily in the northern third and on the extreme southeastern edge of the aquifer. The Trinity Group produces water in the south from the Hosston, Sligo, Cow Creek, Hensell and Glen Rose Formations, while in the north where the Glen Rose pinches out, all of the Trinity Group is referred to as the Antlers Sand. The saturated thickness of the entire aquifer is generally less than 400 feet, although the maximum thickness can exceed 1,500 feet. A cross section of the Edwards-Trinity (Plateau) aquifer is shown in Figure 12.

Groundwater in the Edwards-Trinity (Plateau) aquifer occurs under both confined and unconfined conditions. Recharge is primarily through the infiltration of precipitation on the outcrop, in particular where the limestone formations outcrop. Discharge is to wells and to the Pecos River and Rio Grande in the southwest, the Colorado River in the northeast, and to the Frio, Medina, Nueces, and Guadalupe Rivers in the Hill Country area. Groundwater flow in the Edwards-Trinity (Plateau) aquifer generally flows in a south-southeasterly direction, but may vary locally. The hydraulic gradient averages about 10 feet/mile. Long-term water-level declines have been observed in areas of heavy pumping.

Aquifer properties of the Trinity Group formations vary across the aquifer. Transmissivities range from 1,000 to 10,000 gpd/ft, but average about 3,000 gpd/ft. Storage coefficients for the Trinity formations are estimated to be between 1×10^{-4} to 1×10^{-5}, and specific yields are estimated to be 0.05 to 0.10. Specific capacities of wells range from less than 1 to greater than 20 gpm/ft. Reported well yields commonly range from less than 50 gpm from the thinnest saturated section to 1,500 gpm, although higher yields occur in locations where wells are completed in jointed or cavernous limestone. Due to the nature of groundwater flow in the Edwards, it is very difficult to estimate aquifer properties for this portion of the aquifer. However, based on aquifer characteristics of the Edwards elsewhere, transmissivities are estimated to range from 50,000 to more than 300,000 gpd/ft, storage coefficients are estimated to range from 1 x

10^{-4} to 1 x 10^{-5}, and specific yields are probably 0.01 to 0.02. Overall, the Edwards-Trinity (Plateau) aquifer has been described as having transmissivities of between 35,000 and 40,000 gpd/ft in the northern and eastern sections, and 35,000 to 375,000 gpd/ft in the southern and western sections[2]. These aquifer characteristics are predominantly for the fresh section of the aquifer, in particular from wells producing from the Edwards portion of the aquifer, and they are expected to be lower in the brackish section, which tend to be in the Trinity formations.

The chemical quality of the Edwards and associated limestones is generally better than that in the underlying Trinity aquifer in the Plateau region. Groundwater is fairly uniform in quality, with water from the Edwards and associated limestones being a very hard, calcium bicarbonate type, usually containing less than 500 mg/L TDS, although in some areas the TDS can exceed 1,000 mg/L. The water quality in the Trinity tends to be poorer than in the Edwards. The chemical quality of water from the Antlers is of the calcium bicarbonate/sulfate type and very hard, with salinity increasing towards the west. Salinities in the Antlers typically range from 500 to 1,000 mg/L TDS, although groundwater with greater than 1,000 mg/L TDS is common.

Summary

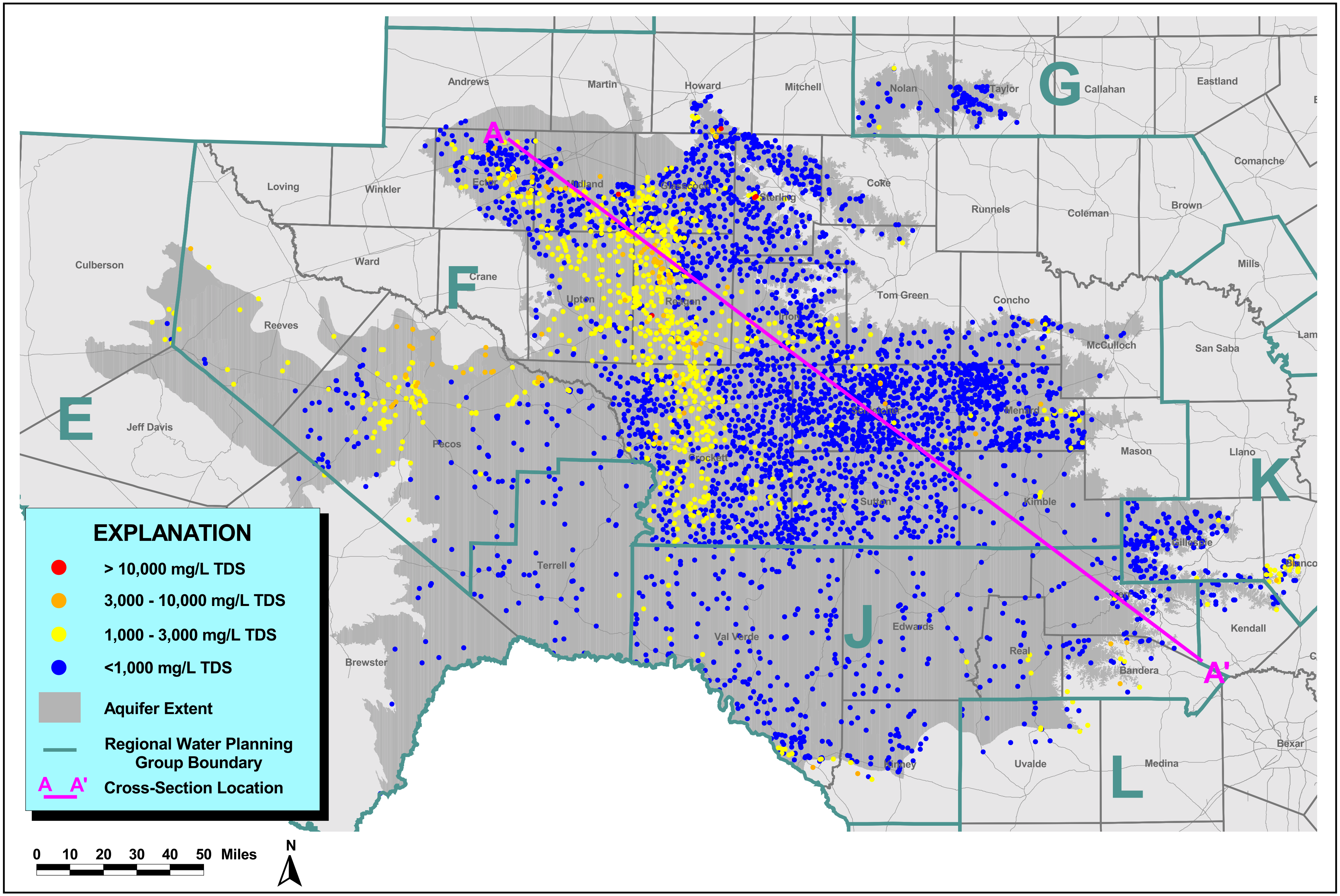
As shown in Figure 11, much of the groundwater found in the Edwards-Trinity (Plateau) aquifer is fresh to slightly-saline. Brackish groundwater appears to mostly be found in the western section of the aquifer, in particular in Reagan, Upton and western Crockett Counties, with lesser amounts in Midland, Ector, Pecos, and Reeves Counties, and in the southwestern edge of the aquifer. In these areas, most of the groundwater production is from the Trinity formations. The brackish groundwater present in the Trinity formations in the lower two-thirds of the aquifer is largely unknown, mainly because few wells penetrate into these formations. In these areas, the Edwards and associated limestones provide sufficient fresh groundwater to meet demands.

Availability- HIGH- In the north, where the Trinity Group formations are used extensively, availability from the Edwards-Trinity (Plateau) aquifer is considered high. In the south, where the Edwards and associated limestones are predominantly used, the availability is unknown, because in this area the availability of brackish groundwater from the Trinity formations is unknown. Groundwater in this area from the Edwards is primarily fresh.

Productivity- LOW- In the northern portion of the aquifer, where the Trinity Group formations would be used for brackish groundwater production, the productivity of the Edwards-Trinity (Plateau) aquifer is low. Relatively shallow wells can be installed in these areas, but transmissivities are relatively low. The productivity of the aqufier in the rest of the area, where the Edwards is the primary groundwater producing unit, is unknown due to the lack of wells penetrating into the Trinity formations where brackish groundwater may be present. However, in these areas it would be expected that the productivity of the Trinity formations would be very low.

Source Water Production Cost- LOW - Shallow wells in the northern portion of the aquifer, producing from the Trinity units, will have a relatively low relative cost for producing groundwater. As with availability and productivity, production costs for Trinity wells in the southern portion of the aquifer, should brackish groundwater exist, is uncertain.

Summary of Brackish Water In the Edwards-Trinity (Plateau) Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
E- Far West Texas	None	--	--
F- Region F	High	Low	Low
G- Brazos	None	--	--
J- Plateau	Unknown	Unknown	Unknown
K- Lower Colorado	None	--	--
L- South Central Texas	None	--	--



GROUNDWATER QUALITY IN THE
EDWARDS-TRINITY (PLATEAU) AQUIFER

FIGURE 11

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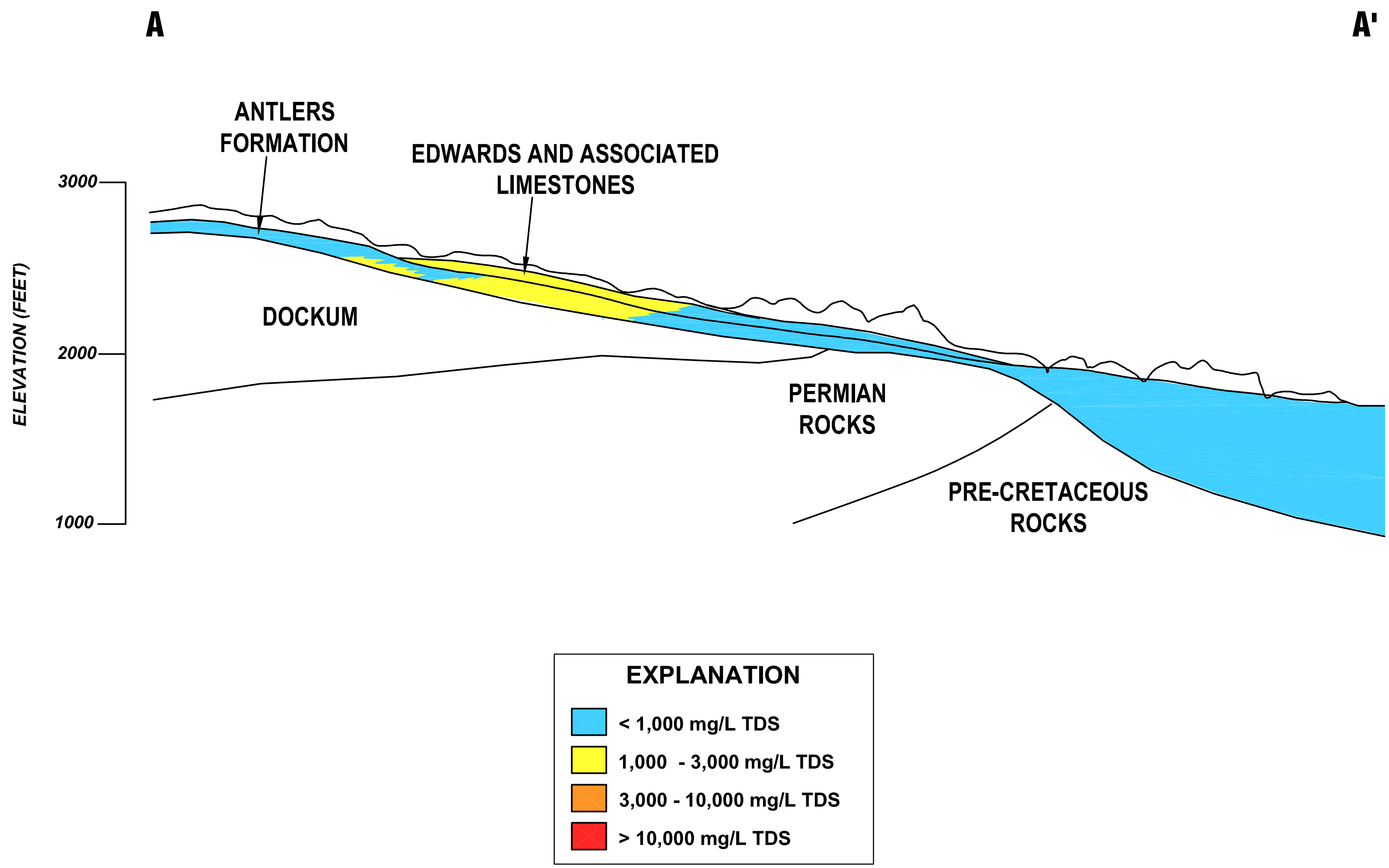


SIMPLIFIED CROSS SECTION OF THE EDWARDS-TRINITY (PLATEAU) AQUIFER WITH GENERALIZED WATER QUALITY RANGES

(Modified from Walker, 1979)

FIGURE 12

LBG-GUYTON ASSOCIATES

3.1.6 Edwards (Balcones Fault Zone)

The Edwards (Balcones Fault Zone-BFZ) aquifer (referred to here as the Edwards aquifer) consists of highly faulted, cavernous, highly transmissive Cretaceous-age limestones. The aquifer is present in twelve counties in Central to South Central Texas, as shown in Figure 13, running from Kinney County in the west to Bell County in the northeast. Groundwater from the Edwards aquifer has been extensively produced for decades. Approximately half of the water produced from the Edwards is used for irrigation, and half for municipal and industrial purposes. The City of San Antonio is the largest municipal user, and the Edwards has been the sole source of water for the city.

Figure 14 shows a generic cross section of the aquifer through Bexar County. The Edwards aquifer consists of the limestones of the Edwards Group as wells as the overlying Georgetown Formation and the Comanche Peak Limestone, where present. The Edwards aquifer is between 200 and 600 feet thick, and is a limestone karst aquifer, with much of the groundwater flow occurring along solution-enlarged openings along joints, faults, and fractures.

Groundwater is present in the Edwards under water-table conditions in the outcrop area and under confined or artesian conditions in the down-dip portion of the formation. It is in the artesian section that most of the groundwater is produced from the Edwards. A groundwater divide present near Kyle in Hays County divides the aquifer into two separate hydrologic regions. The region to the west is known as the San Antonio region, and the region to the northeast is known as the Austin or Barton Springs region. Because of the karstic nature of the Edwards aquifer, it responds very quickly both to pumpage and to recharge. Recharge occurs mainly through the infiltration of precipitation that runs off into local streams and rivers. Much of the recharge occurs in very short periods of time that occur with high precipitation events typical of this area of the state. Discharge is to several very large springs emanating from the aquifer and to pumpage. The largest springs in the state issue from the Edwards aquifer.

Transmissivities in the Edwards can be in the millions of gpd/ft, and porosities are typically between 5 and 15%. However, aquifer properties can vary significantly, depending on the nature and extent of fractures and joints encountered in a well bore. Wells drilled into the Edwards can be some of the most productive wells in the world, with one flowing artesian well producing in excess of 30,000 gpm. City of San Antonio municipal wells can easily produce thousands of gallons per minute, with little drawdown. However, these characteristics are for the freshwater section of the aquifer, which may differ significantly from the brackish/saline section of the aquifer. Aquifer characteristics of the saline section of the Edwards are poorly understood because this portion of the aquifer has few wells, but are generally considered to have lower transmissivities, probably ranging from 5,000 to 100,000 gpd/ft, although recent tests indicate that in places, transmissivities in the saline zone may be higher than this (personal communication with san Antonio Water System, 2003). Storage coefficients for the saline portion of the Edwards are estimated to be 1×10^{-4}.

The boundary between the fresh-water and brackish sections of the Edwards aquifer is commonly referred to as the "Bad Water Line", which is the 1,000 mg/L TDS line shown in Figure 13. In places, water quality tends to quickly deteriorate from the Bad Water Line into saline portions of the aquifer, resulting in a fairly small zone of slightly- to moderately-saline water, as shown in Figure 13. However, in other places the moderately-saline zone can be relatively wide. The location of the Bad Water Line is constantly being refined as more study is conducted on the location and nature of this feature. The Bad Water Line in the San Antonio region shown in Figure 13 represents the latest mapping of this feature as of June 2001 (personal communication with San Antonio Water System, June 2001).

Groundwater in the fresh portion of the Edwards is a hard, calcium-bicarbonate water. As the salinity of the water increases in the saline portion of the aquifer, the concentrations of sulfate and chloride increase, as does the concentration of sodium, and the waters become a sodium-mixed anion type water. The quality of the saline water in the Edwards aquifer does not appear to vary significantly areally. In general, poorer quality water in the aquifer is found in the down-dip portions of the aquifer, and may also correlate with low permeability sections of the formations. Similarly, there are no consistent vertical trends in water quality. In places, wells produce fresh water at shallow depths, brackish to saline water at greater depths, and fresh water again at even greater depths. Hydrogen sulfide is often found in the Bad Water Zone.

Summary

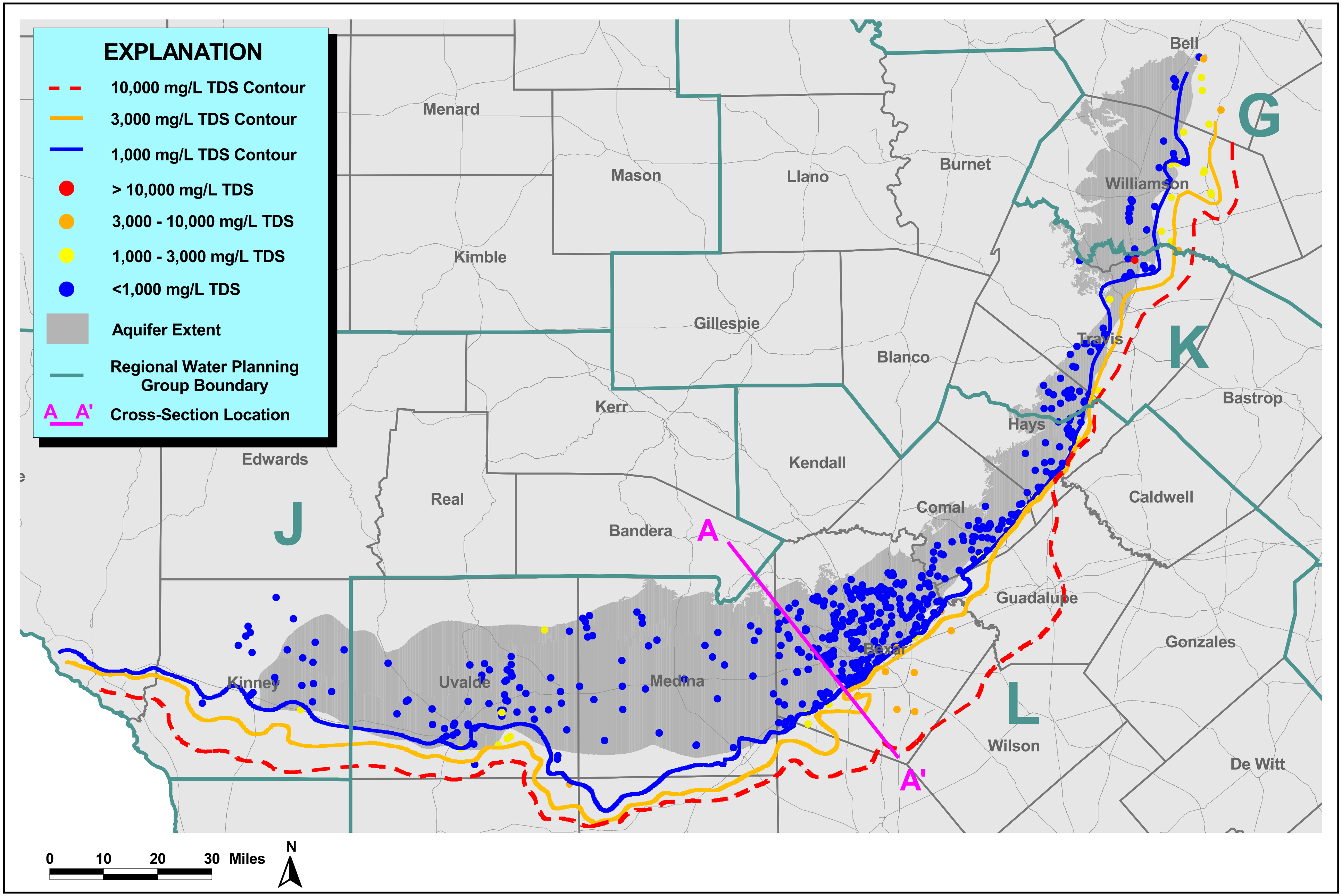
The Edwards aquifer offers an important potential brackish groundwater resource for exploration and development. A significant amount of brackish water may be available from the aquifer, as shown in Figure 14. However, several potential problems exist with the use of these brackish groundwater resources. First is that brackish water in the Edwards is typically found in the less permeable portions of the aquifer, which limits the amount that can be produced from each well. However, exceptions to this have occurred, and some wells installed in the saline portion of the aquifer have produced significant quantities of water. A second potential problem with the use of brackish water from the Edwards is the impact that production from the brackish section has on water levels in the fresh section, in particular in the San Antonio area where the demand for Edwards groundwater is the highest. The Edwards aquifer contains large volumes of fresh groundwater, however legal limitations have been placed on the amount of water that can be produced, and the water levels that must be maintained in certain index wells in the fresh section. If the production of brackish groundwater from the Edwards impacts water levels in the fresh section, then the use of the brackish groundwater could be counterproductive. A third problem is the presence of hydrogen sulfide in the more saline portions the Edwards. Hydrogen sulfide may result in corrosion problems, and brackish groundwater would have to be pretreated to remove hydrogen sulfide before being desalinated with reverse osmosis technology.

<u>*Availability*</u>- LOW to HIGH- Most of the brackish groundwater available from the Edwards aquifer is found in the Region L area, which includes most of the San Antonio portion of the aquifer. Although the slightly- to moderately-saline section in this area is relatively thin (laterally), a significant amount of water may be available from the Edwards in this area. In other areas, the Edwards is less extensive, and is not considered to be as good a potential source as in the San Antonio area.

Productivity- LOW to MODERATE- Although the brackish section is relatively narrow, there may be a significant amount of brackish groundwater available. The brackish, or "Bad Water" zone of the Edwards has variable aquifer characteristics. In general the Edwards is much less transmissive in the saline section than the rest of the aquifer. However, some very productive wells are present in this portion of the aquifer.

Source Water Production Cost- MODERATE to HIGH- Because brackish water in the Edwards aquifer occurs in the down-dip portions of the aquifer, wells installed to produce brackish water will typically be very deep. In addition, because brackish water is typically found in lower permeability sections of the aquifer, production from wells may be low to moderate, and a larger number of deep, expensive wells may be necessary to produce the required volume of brackish groundwater.

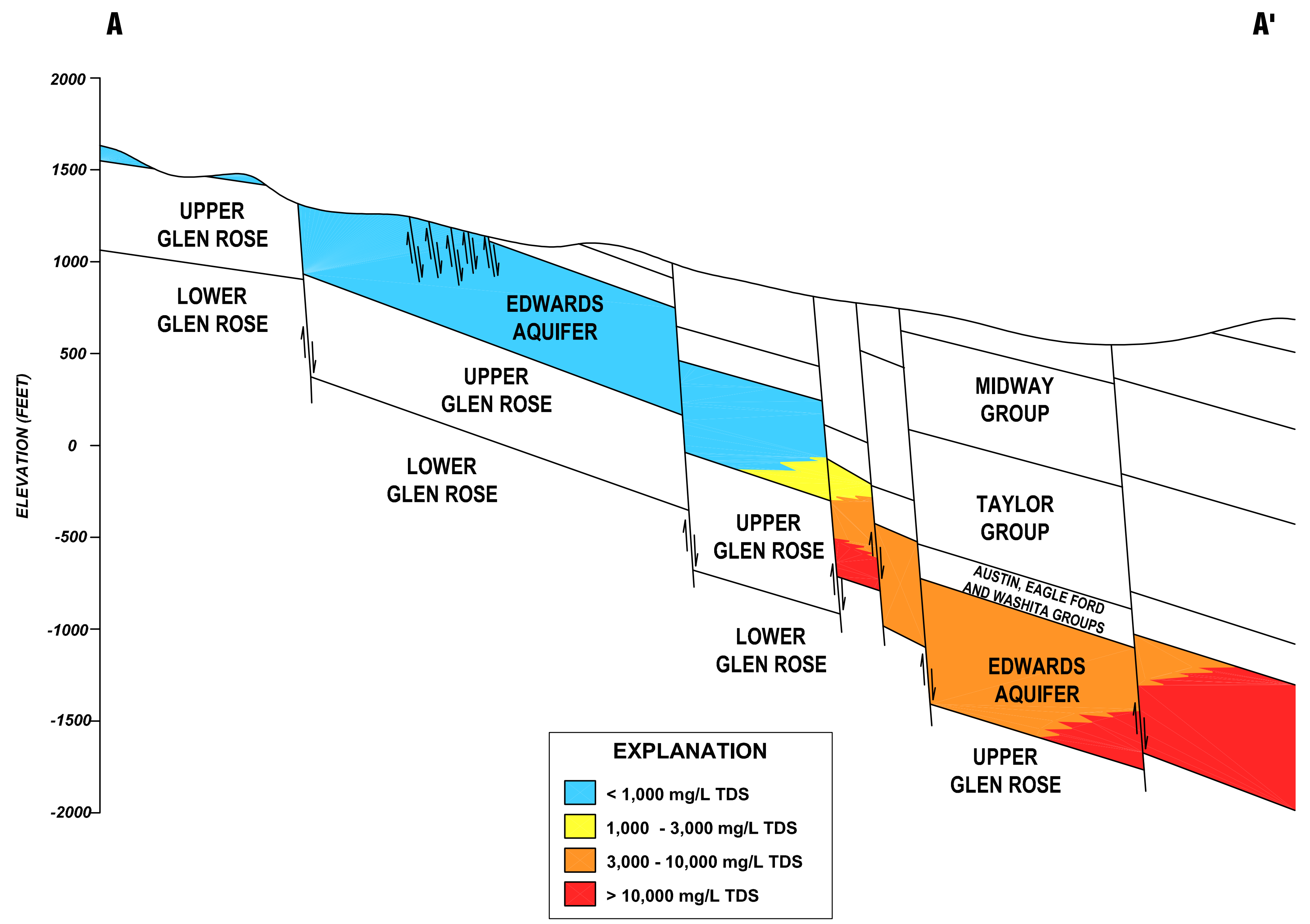
Summary of Brackish Water In the Edwards (BFZ)Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
G- Brazos	Moderate	Low to Moderate	Moderate to High
J- Plateau	Low to Moderate	Low to Moderate	Moderate to High
K- Lower Colorado	Low to Moderate	Low to Moderate	Moderate to High
L- South Central Texas	High	Low to Moderate	Moderate to High



GROUNDWATER QUALITY IN THE
EDWARDS (BALCONES FAULT ZONE) AQUIFER

FIGURE 13

LBG-GUYTON ASSOCIATES



SIMPLIFIED CROSS SECTION OF THE EDWARDS (BFZ) AQUIFER WITH GENERALIZED WATER QUALITY RANGES
(Modified from Small, 1986 and Maclay and Small, 1984)

FIGURE 14

LBG-GUYTON ASSOCIATES

3.1.7 Trinity

The Trinity aquifer is actually an aquifer system composed of individual aquifers that are contained within the geologic formations that comprise the Cretaceous-age Trinity Group. The Trinity aquifer is located in an area extending from central to north-central Texas, as shown in Figure 15. Trinity Group formations are also present in the Texas Panhandle and Edwards Plateau regions, but there they are classified as part of the Edwards-Trinity (High Plains and Plateau) aquifers, and are described separately in this report. Groundwater produced from the Trinity aquifer is used for irrigation, municipal, industrial, domestic, and livestock purposes.

Trinity Group deposits include sands, limestones, shales and clays. The stratigraphy of the Trinity Group is complicated, in part because of the large area that it covers. Although many of the formations of the Trinity Group extend through much of the area shown in Figure 15, these units have different names, or are described in different ways, in different parts of the state. The correlation between geologic units of the Trinity for the different regions is shown in Figure 16. Three generalized cross sections shown in Figures 17, 18, and 19 show the lateral changes in the main areas of the Trinity.

Recharge to the Trinity aquifer is through the infiltration of precipitation on the outcrop. Groundwater flow is generally from these outcrop areas to the east or southeast, in a down-dip direction. Discharge from the aquifer is to rivers and streams and to wells. In South Central Texas, which includes the Hill Country and the Balcones Fault Zone area, the Trinity aquifer is heavily produced, both from the "Middle Trinity", consisting of the Lower Glen Rose, Hensell Sand, and the Cow Creek Limestone, and from the "Lower Trinity", consisting mostly of the Hosston Sand. Transmissivities for the Middle Trinity vary significantly. In some areas they are as high as 60,000 gpd/ft, but in many areas are less than 1,000 gpd/ft. In the "Lower Trinity", the Hosston Sand is an important source of water for the cities of Bandera and Kerrville. The Hosston can have transmissivities up to 40,000 gpd/ft, and is capable of yielding moderate to large quantities of water to wells, but only in limited areas. Specific yields in South Central Texas are expected to be 0.02 to 0.05, and storage coefficients are 1×10^{-4} to 1×10^{-5}.

In Central Texas, the Hensell and Hosston Sands are the most productive units in the Trinity aquifer. The Hensell is fairly prolific in many areas, and is known to yield small to large amounts of water to wells. It is also referred to as the "First" or "Upper" Trinity Sand by drillers and locals in Central Texas. Here the average transmissivity of the Hensell is less than 2,000 gpd/ft. The Hosston thickens significantly in the down-dip areas and transmissivities can be as high as 45,000 gpd/ft. In Central Texas, specific yields are estimated to be 0.05 to 0.10 for the lower units, with storage coefficients of 1×10^{-4} to 1×10^{-5}.

The Trinity is the largest and most prolific aquifer in North Central Texas. Extensive development of the aquifer has occurred in the Dallas-Fort Worth region where water levels have declined more than 500 feet in some areas. Trinity aquifer transmissivities in the fresh water section in this area range from less than 4,000 gpd/ft to more than 14,000 gpd/ft. Confined storage coefficients are between 1×10^{-4} and 5×10^{-4}, and unconfined specific yields are between 0.15 and 0.25. Wells completed in the Trinity in the northern section are capable of producing up to 2,000 gpm.

Groundwater is produced from the Antlers Sand in the western outcrop extent of the Trinity Group in the Central and North-Central regions. Transmissivities in the Antlers range from to 6,000 to 18,000 gpd/ft, with yields to wells as high as 900 gpm. Higher yields are found in wells that fully penetrate the aquifer. Confined storage is about 2.5×10^{-4}, and unconfined specific yields are 0.20 to 0.25.

Because the Trinity aquifer is comprised of several individual smaller layered aquifers, the location of slightly- to moderately-saline water within the aquifer extent is quite variable. Water of poor quality may be found at one location above and/or beneath another layer of good water quality. In many cases, areas may contain wells that produce slightly- and moderately-saline water adjacent to wells that produce fresh water from another zone in the Trinity aquifer. Finer-grained sediments are typically found further down-dip, which results in lower permeabilities in the down-dip direction. This, along with greater distance from recharge zones, results in increasing salinities in the down-dip direction. In general, because of the poorer water quality, lower production, and increasing well depths, almost no water wells are constructed in the Trinity down-dip areas. Water quality must be inferred from geophysical logs performed mostly on oil and gas wells. Figure 15 shows the inferred 1,000 mg/L, 3,000 mg/L, and 10,000 mg/L TDS concentration.

Summary

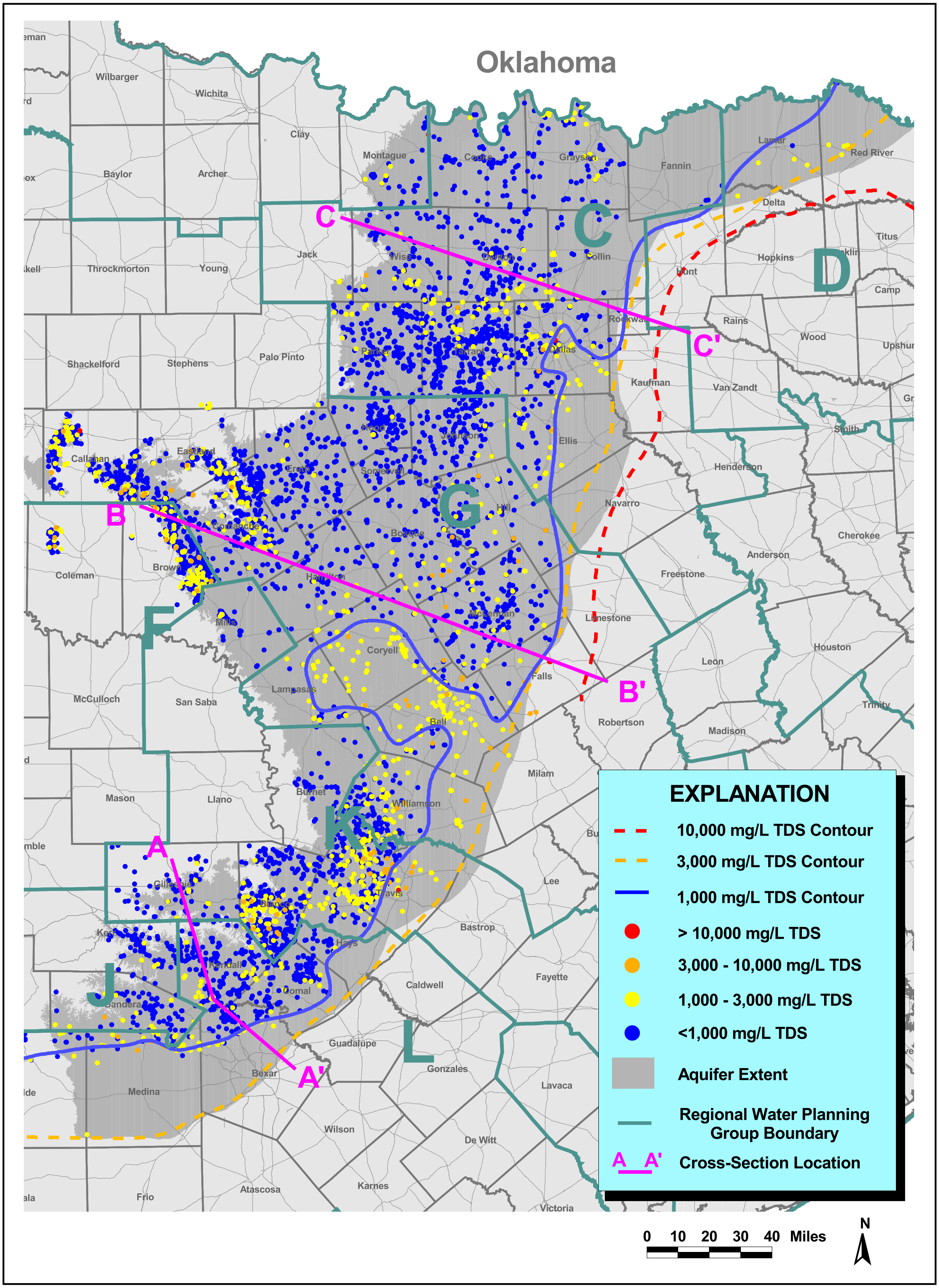
A significant source of brackish water may be found in the down-dip areas of the Trinity aquifer. However, the wells completed in these locations will probably be relatively deep and lower producing because of decreasing permeabilities found in these areas of the aquifer where the brackish water is present. In other areas of the aquifer, small to moderate volumes of brackish groundwater may be developed in the future. However, these areas will likely be limited in areal and vertical extent because of the spotty presence of the brackish water throughout the aquifer area.

Availability- MODERATE- The availability of brackish groundwater from the Trinity aquifer in most of region is considered to be moderate. Availability in Region F is considered to be low due to the limited extent of the Trinity aquifer in this region.

Productivity- LOW to MODERATE- In general, the productivity of the Trinity aquifer is low. Brackish groundwater is likely to be found at greater depths, where the aquifer tends to be less transmissive.

Source Water Production Cost- MODERATE to HIGH- Due to the deeper, less transmissive nature of the brackish sections of the Trinity aquifer throughout most of its extent, relative source water production costs are expected to be moderate to high. The relative cost for Region F will be low because the brackish groundwater, if available, will be found at shallower depths.

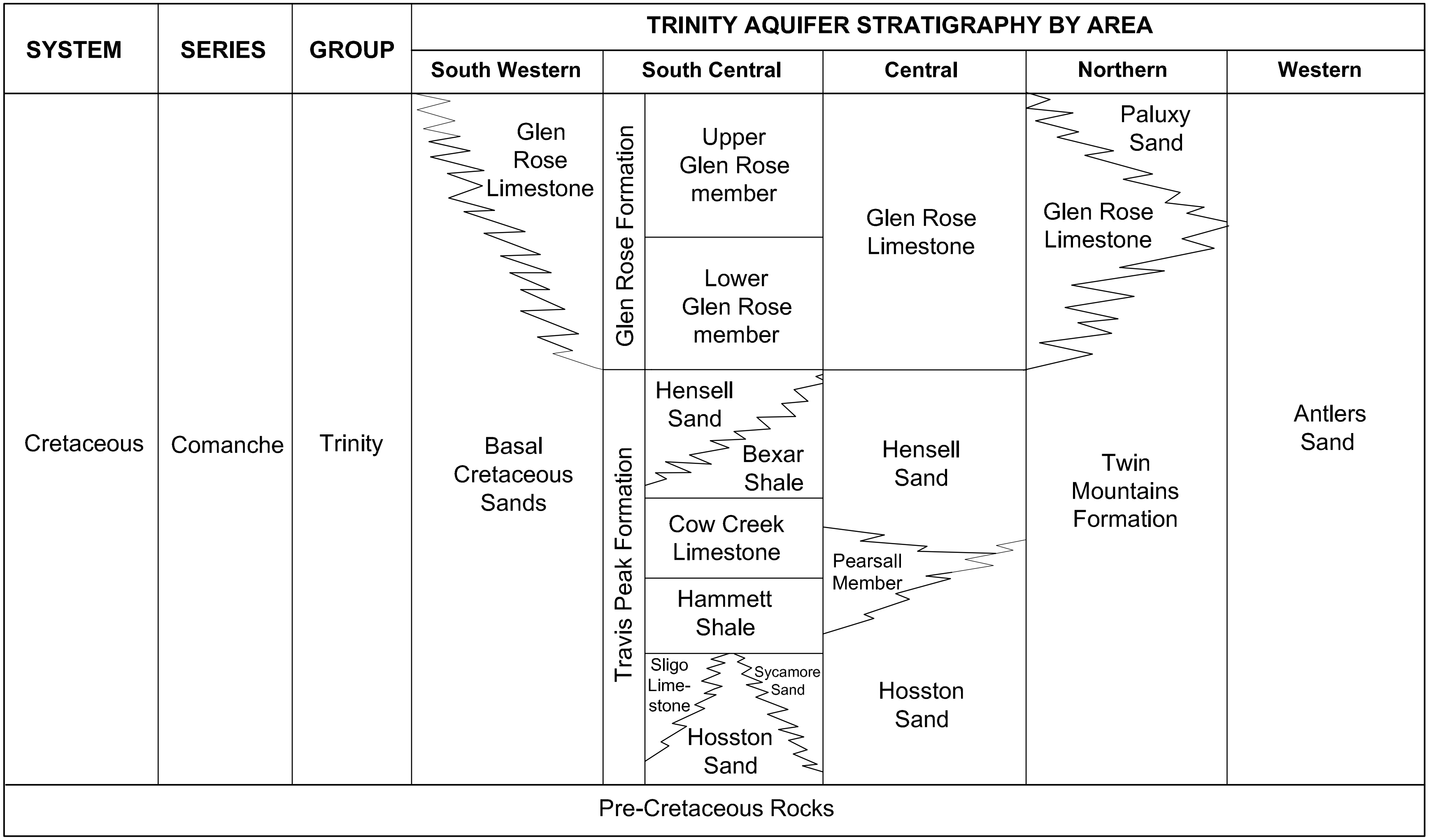
Summary of Brackish Water In the Trinity Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
B- Region B	None	--	--
C- Region C	Moderate	Low	Moderate to High
D- North East Texas	None	--	--
F- Region F	Low	Low	Low
G- Brazos	Moderate	Moderate	Moderate to High
J- Plateau	Moderate	Low	Moderate to High
K- Lower Colorado	Moderate	Low	Moderate to High
L- South Central Texas	Moderate	Low	Moderate to High



GROUNDWATER QUALITY IN THE TRINITY AQUIFER

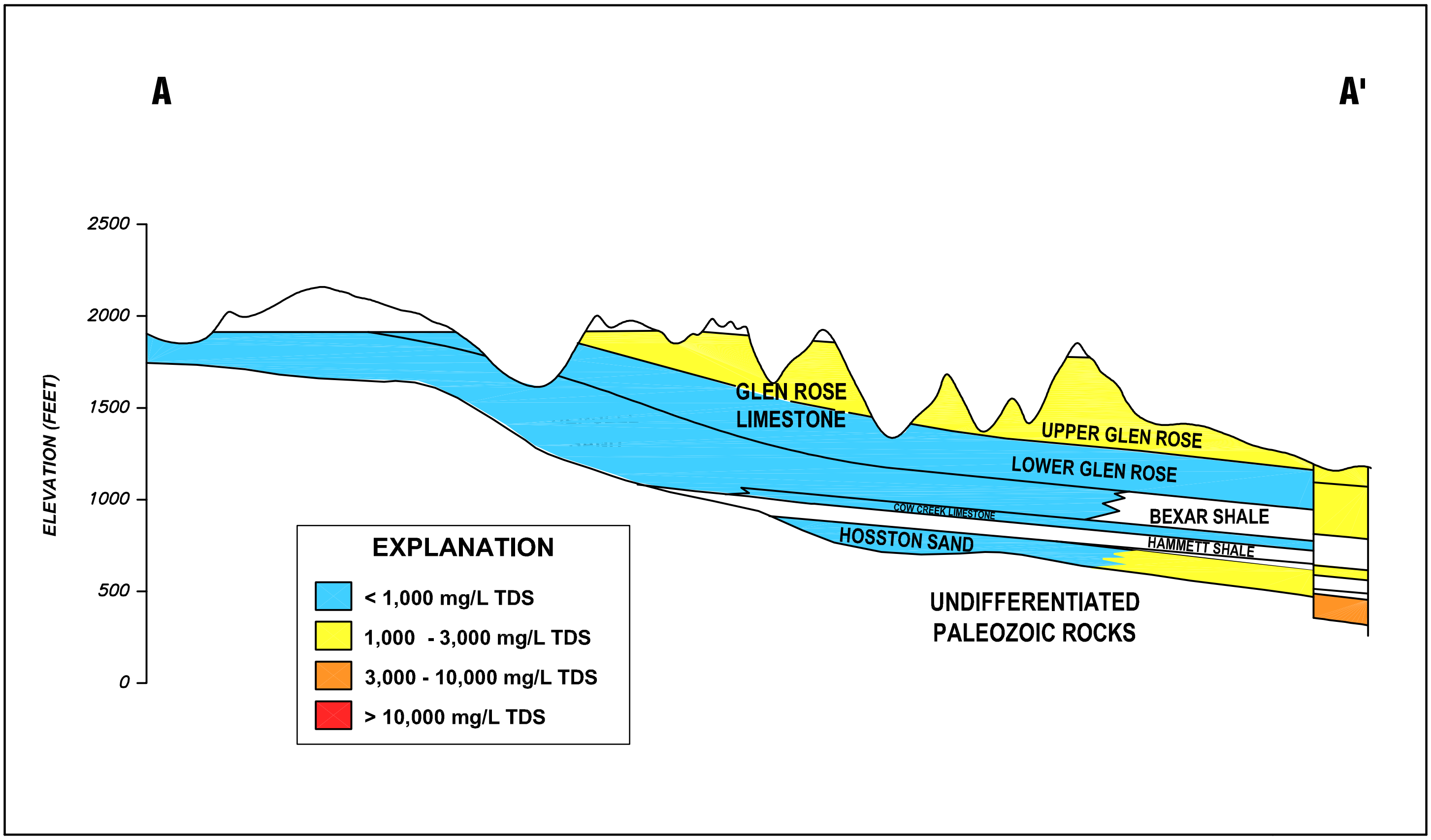
FIGURE 15

LBG-GUYTON ASSOCIATES



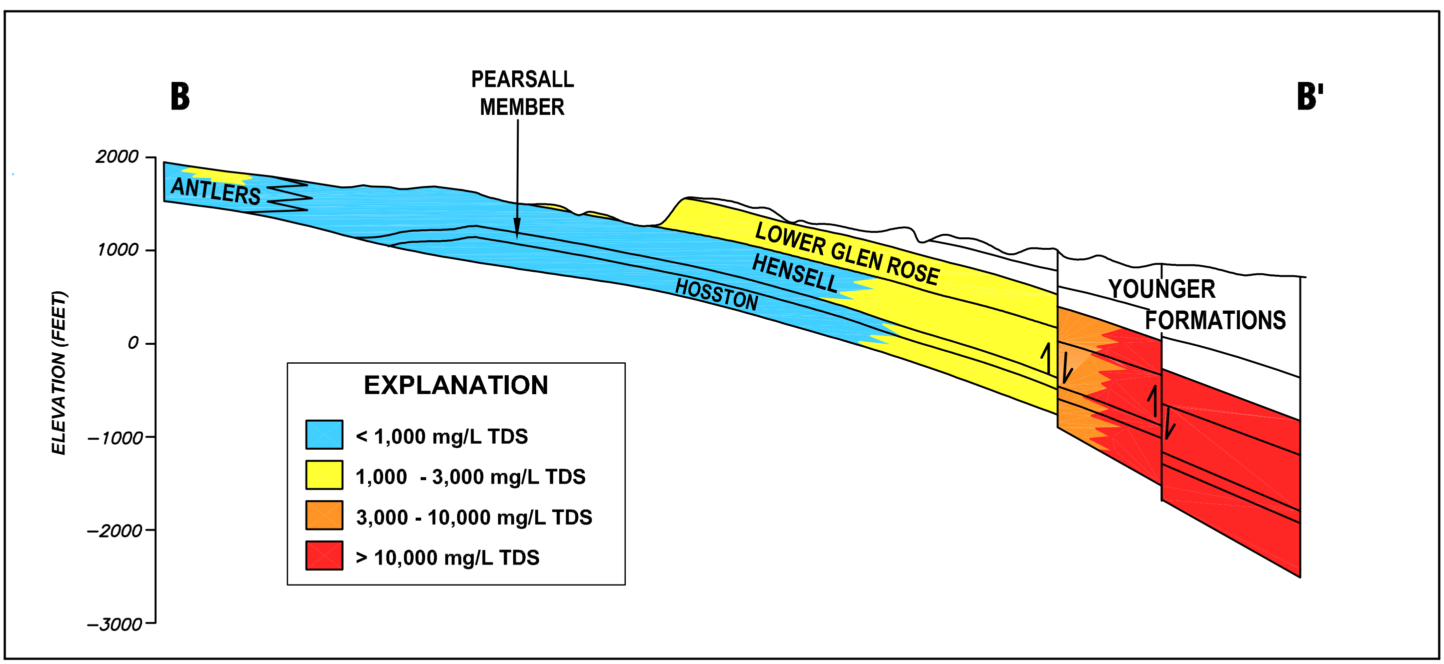
STRATIGRAPHIC CORRELATION OF THE TRINITY AQUIFER **FIGURE 16**

LBG-GUYTON ASSOCIATES



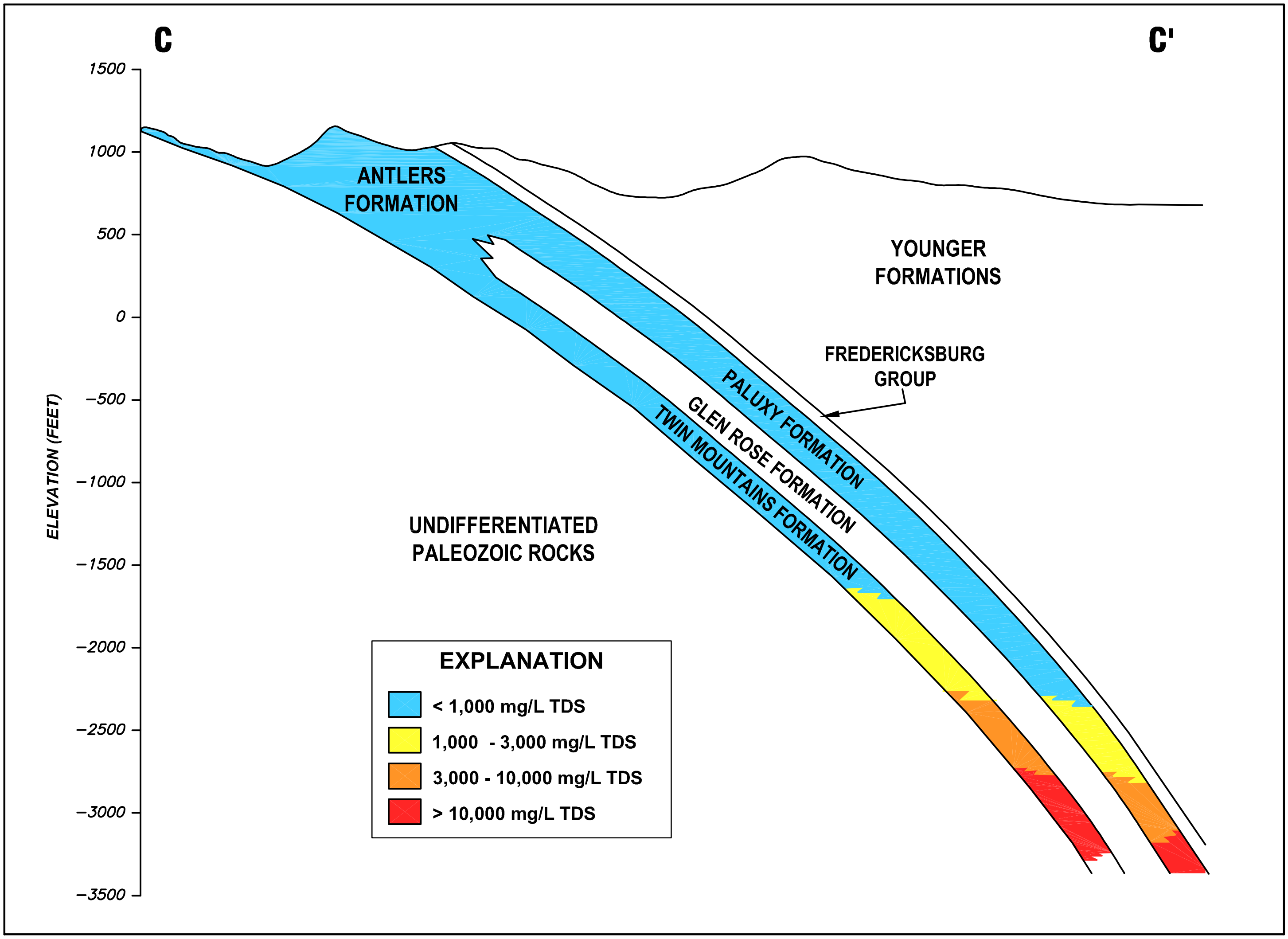
SIMPLIFIED CROSS SECTION A-A' OF THE TRINITY AQUIFER WITH GENERALIZED WATER QUALITY RANGES
(Modified from Ashworth, 1985)

FIGURE 17



SIMPLIFIED CROSS SECTION B-B' OF THE TRINITY AQUIFER WITH GENERALIZED WATER QUALITY RANGES
(Modified from Klemt and others, 1975)

FIGURE 18



SIMPLIFIED CROSS SECTION C-C' OF THE TRINITY AQUIFER WITH GENERALIZED WATER QUALITY RANGES
(Modified from Nordstrom, 1982)

FIGURE 19

3.1.8 Carrizo-Wilcox

The Carrizo-Wilcox aquifer is one of the most extensive and productive aquifers in Texas, stretching from the Rio Grande to the Texas/Louisiana/Arkansas border, as shown in Figure 20. The aquifer provides a significant amount of fresh water for irrigation, industrial and public water supplies. In the subsurface, the Carrizo and Wilcox sands are sometimes difficult to distinguish from each other, and they are often hydraulically interconnected, and therefore the term "Carrizo-Wilcox aquifer" is often used.

The Carrizo-Wilcox aquifer consists of hydrologically connected, Tertiary age, interbedded sands, clays, silts, and some discontinuous lignite beds of the Wilcox Group and the overlying massive sands of the Carrizo Sand. Overlying the aquifer are the shales and clays of the Reklaw Formation in East and Central Texas, and the sands and clays of the Bigford Formation in South Texas, which serve as the confining units over the Carrizo-Wilcox. The thickness of the Carrizo-Wilcox varies widely across the state. In South Texas, saturated thickness in the outcrop is generally less than 100 feet, and in down-dip sections reaches only a maximum of 500 feet. In South Central Texas, the aquifer thickens significantly, with as much as 700 feet of saturated thickness in the outcrop areas and up to 2,000 feet in down-dip portions of the aquifer. In Central Texas, the aquifer thins somewhat, with outcrop saturated thickness of less than 500 feet, and thickness down-dip of 1,000 to 1,500 feet. In East Texas, saturated thickness in the outcrop is generally less than 500 feet and down-dip thickness is a maximum of 1,000 feet. Four general cross sections for the Carrizo-Wilcox are shown in Figures 21 to 24.

Groundwater from the Carrizo-Wilcox aquifer is extensively used in many regions of the state, although the specific zones of the aquifer from which groundwater is produced varies. In South Texas, the Carrizo Sand is the preferred source of groundwater with only minor amounts of water being withdrawn from the sand and clays of the underlying Wilcox. Both the Simsboro Formation of the Wilcox Group and the Carrizo Sand are utilized extensively for groundwater purposes in Central Texas. In East Texas groundwater is produced from the "Carrizo-Wilcox", as the differentiation of the individual units within the Wilcox, and between the Carrizo and Wilcox, becomes difficult. Recharge to the Carrizo-Wilcox is through the infiltration of precipitation in the outcrop and from rivers and streams flowing across the outcrop area. Groundwater flow is from the outcrop areas down-dip into the subsurface. Historically, discharge from the Carrizo was through leakage to overlying formations and also to springs, however currently discharge is mostly to wells completed in the aquifer.

Aquifer properties of the Carrizo-Wilcox aquifer vary across the state. In South Texas, transmissivities are relatively low, ranging from 5,000 to 10,000 gpd/ft. In South Central and Central Texas, transmissivities are much higher, and can range from 50,000 to 150,000 gpd/ft. In East Texas transmissivities are high, ranging from 30,000 to 50,000 gpd/ft. In general, the interbedded sands and clays of the Wilcox are less permeable than those of the Carrizo aquifer. Coefficients of storage for the Carrizo-Wilcox aquifer range from about 0.0001 to 0.001 in the artesian areas, and unconfined specific yields range from 0.05 to 0.30. Well yields from the more transmissive sections of the Carrizo-Wilcox can be thousands of gallons per minute. These characteristics are from the fresh sections of the aquifer, and the aquifer is generally expected to be slightly less prolific in the down-dip areas where slightly- to moderately-saline water is found.

As shown in Figure 20, fresh water is found in the outcrop areas and up to 40 miles down-dip from the outcrop areas throughout much of the extent of the aquifer in the state. Only in South Texas is fresh water not found in the outcrop areas of the aquifer. In general, salinities increase farther down-dip, with fresh water generally being found in outcrop areas and at shallow depths, while slightly-saline water is found at depths ranging from about 3,000 to 4,000 feet, and moderately-saline water at depths ranging from about 3,000 to 6,000 feet. As salinities increase down-dip, the water chemistry varies across the state. In South Texas, the Wilcox yields a mixed water type (both sodium sulfate and sodium chloride), while the Carrizo is principally sodium chloride and sodium sulfate. In Central Texas groundwater from the Carrizo is principally sodium chloride and sodium sulfate types. In South Central Texas, the Carrizo yields slightly-saline sodium bicarbonate water to wells. In East Texas, the dissolved solids in groundwater of the Wilcox consist mainly of sodium, bicarbonate, and chloride.

Summary

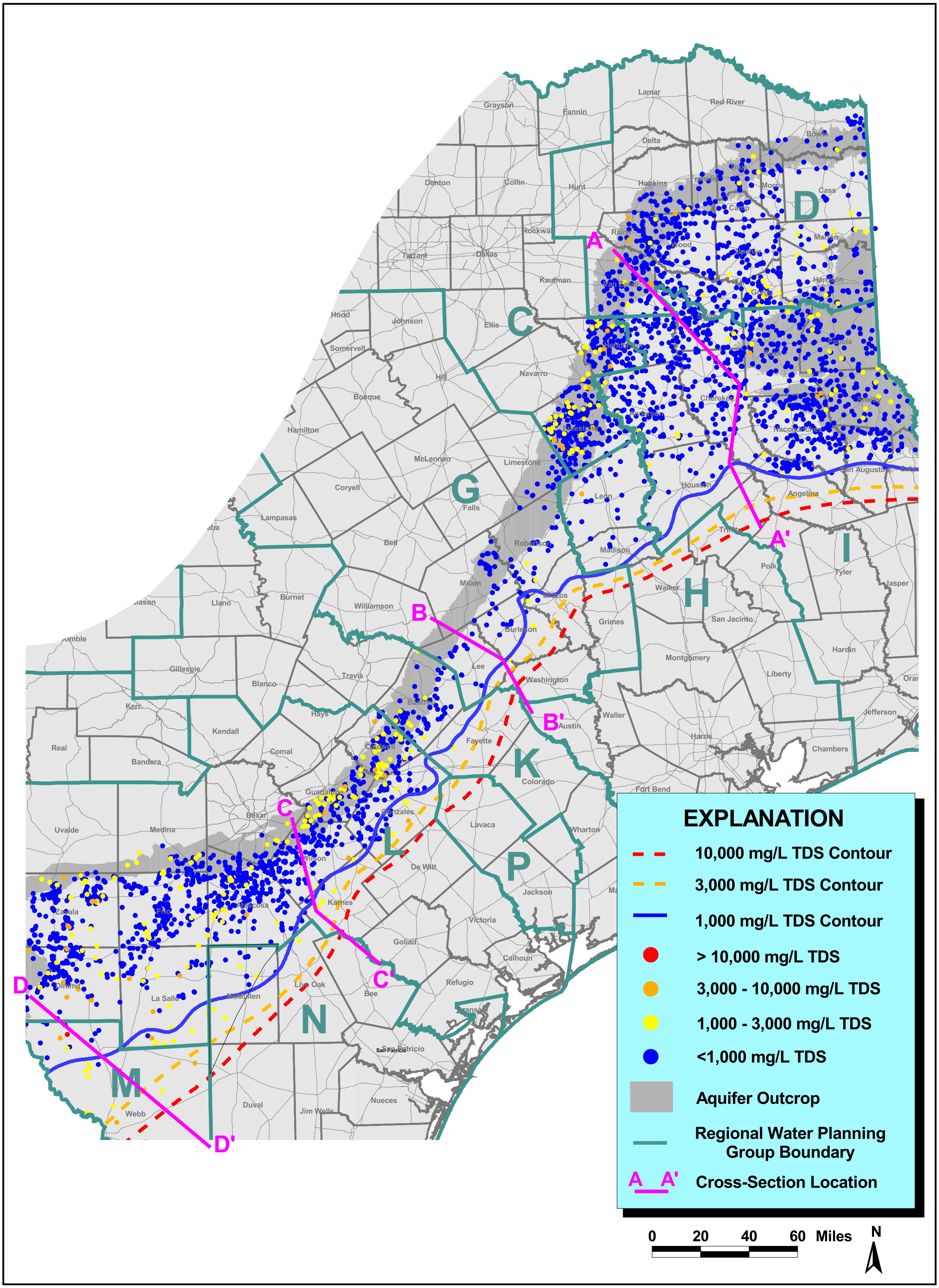
The Carrizo-Wilcox aquifer is one of the most continuous and permeable water-bearing formations in Texas. Throughout the extent of the aquifer, it provides groundwater acceptable for most irrigation, public supply and industrial purposes. It also has significant brackish water resources in down-dip portions of the aquifer that may be used as additional water supplies. The Carrizo-Wilcox should be considered as one of the best potential sources for brackish water in Texas. The hydraulic characteristics (transmissivity and storage) are generally excellent in the fresh water sections of the aquifer, although they may be slightly diminished in the brackish areas. Except in far South Texas, the occurrence of brackish water in and near the outcrop of the aquifer is sporadic and limited.

Availability- HIGH- The Carrizo-Wilcox covers a large area of the state, with a large variation in aquifer thicknesses and hydraulic properties. In South Texas, where transmissivities and thicknesses are lower, availability is low, despite the presence of brackish groundwater in the outcrop areas of the aquifer. In South Central Texas, where the aquifer is much more transmissive and thicknesses can be up to 2,000 feet, the availability of brackish groundwater is high. In Central and East Texas, the availability is also high. Although the aquifer is thinner in this area, it can still be as much as 1,500 feet thick, and hydraulic properties are relatively high.

Productivity- MODERATE to HIGH- The Carrizo-Wilcox is capable of yielding significant quantities of water to wells, and is a heavily used aquifer in the state for fresh groundwater. Where brackish groundwater is available, the aquifer will be less transmissive than in the fresh water section, but still quite productive. In South Texas, both the availability and productivity of producing brackish groundwater is low.

Source Water Production Cost- MODERATE to HIGH- Because depths to brackish groundwater in the Carrizo-Wilcox may be 3,000 to 6,000 feet, costs to produce this water are expected to be relatively high.

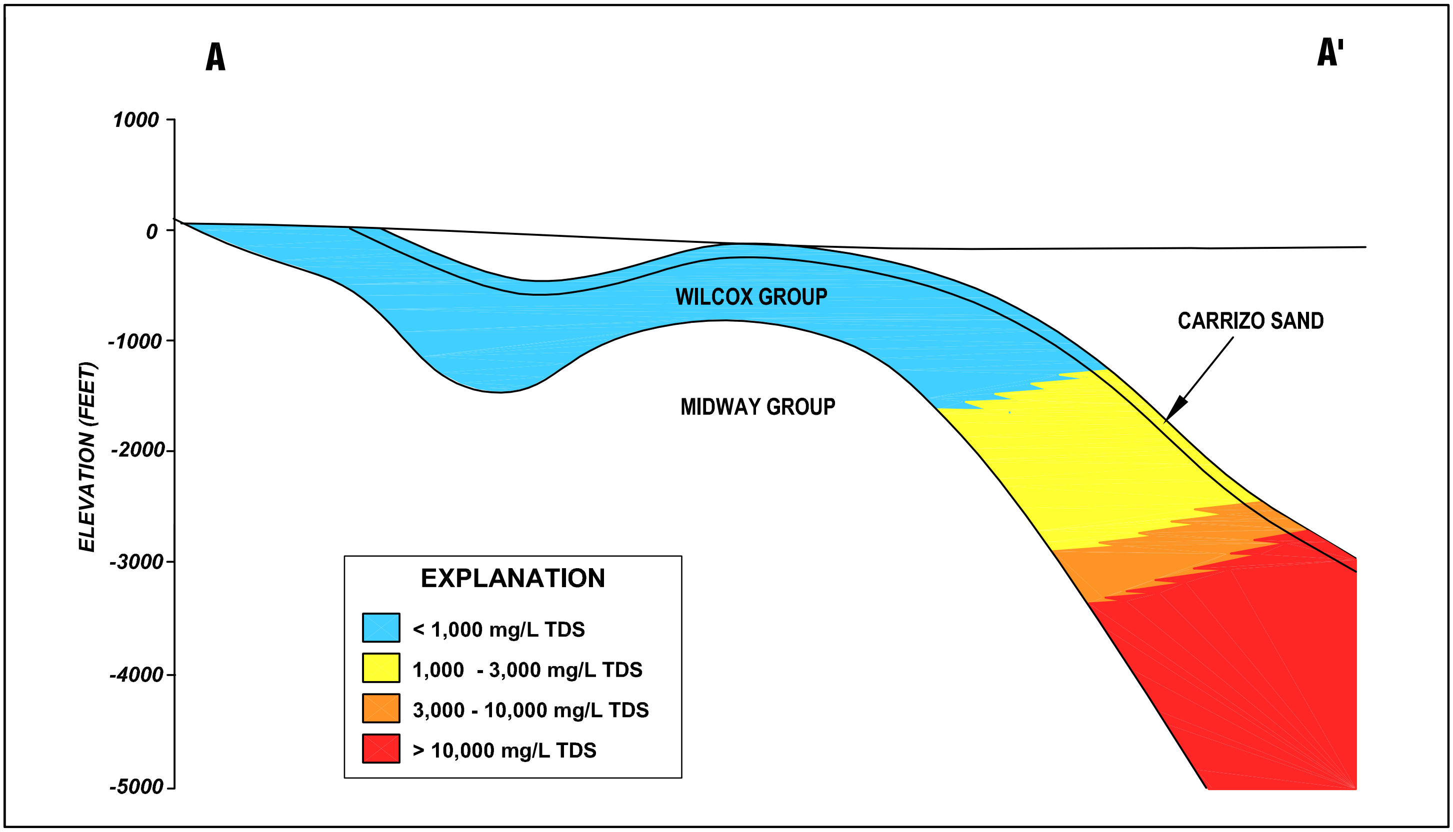
Summary of Brackish Water In the Carrizo-Wilcox Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
C- Region C	None	--	--
D- Northeast Texas	High	Moderate	Moderate to High
G- Brazos	High	Moderate	Moderate to High
H- Region H	Moderate	Moderate	Moderate to High
I- East Texas	High	Moderate	Moderate to High
K- Lower Colorado	High	Moderate	Moderate to High
L- South Central Texas	High	High	Moderate to High
M- Rio Grande	Low	Low	High
N- Coastal Bend	Low	Moderate	High
P- Lavaca	None	--	--



GROUNDWATER QUALITY IN THE CARRIZO-WILCOX AQUIFER

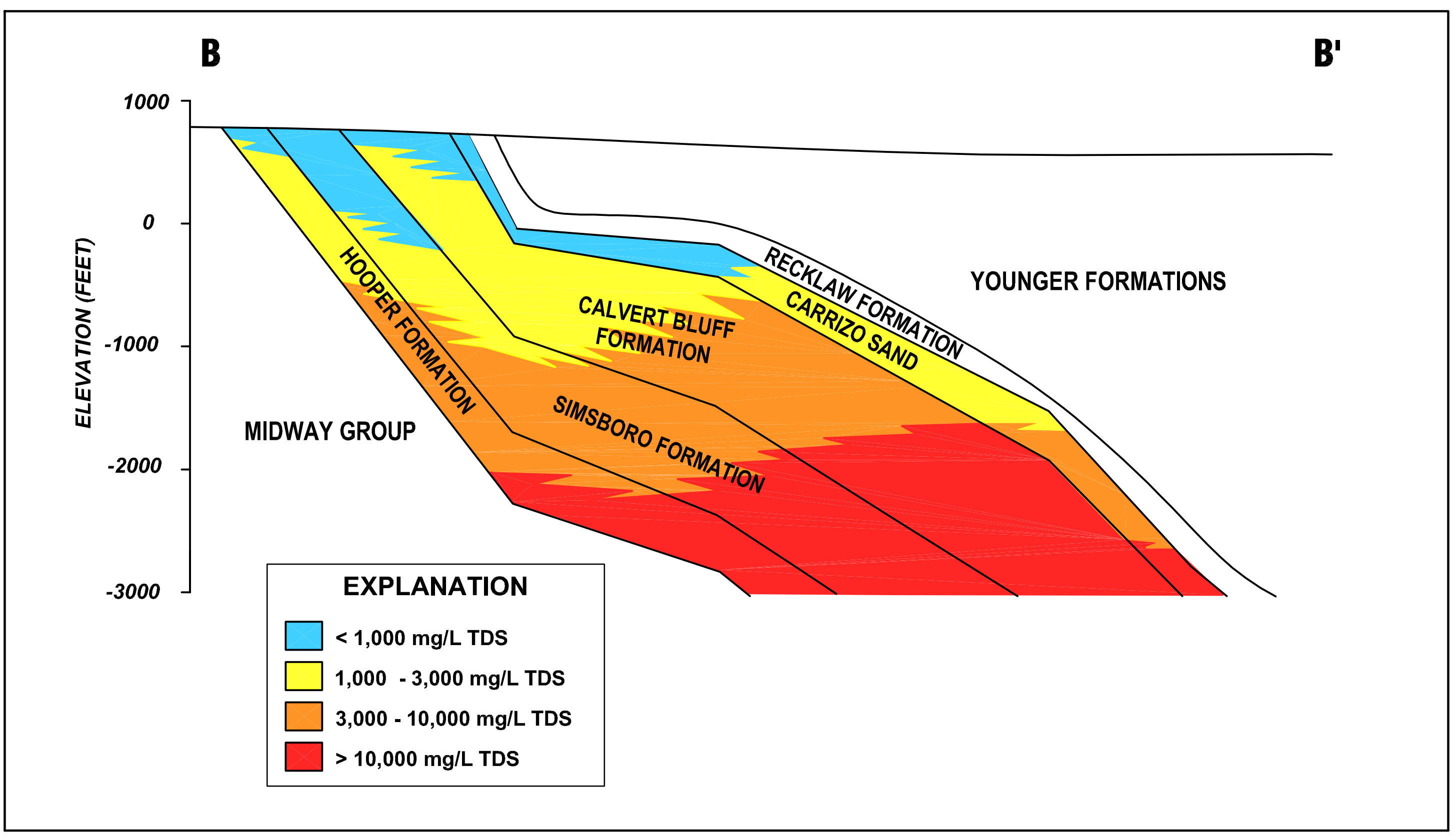
FIGURE 20

LBG-GUYTON ASSOCIATES



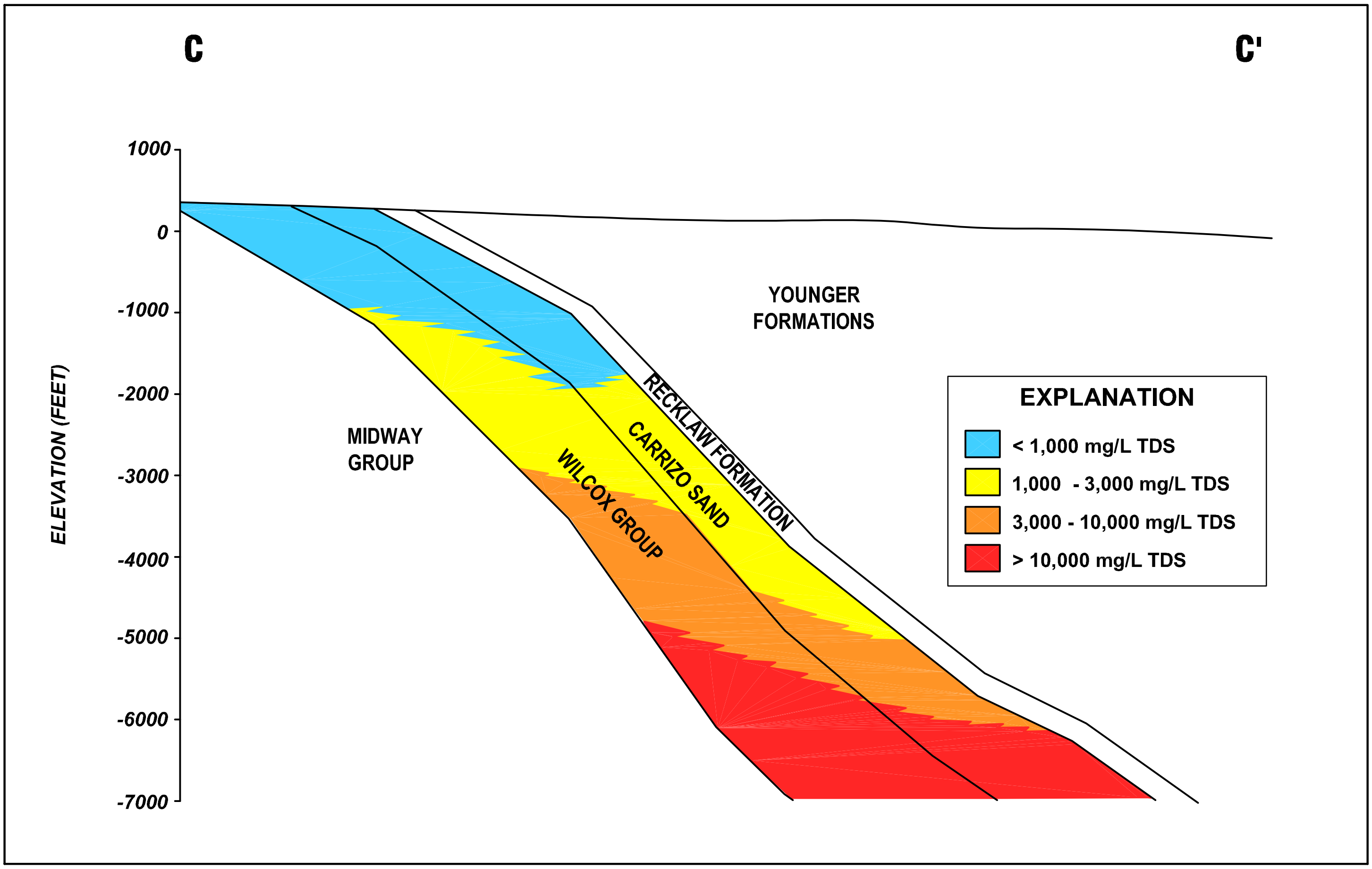
SIMPLIFIED CROSS SECTION A-A' OF THE CARRIZO-WILCOX AQUIFER WITH GENERALIZED WATER QUALITY RANGES
(Modified from Baker, 1979)

FIGURE 21



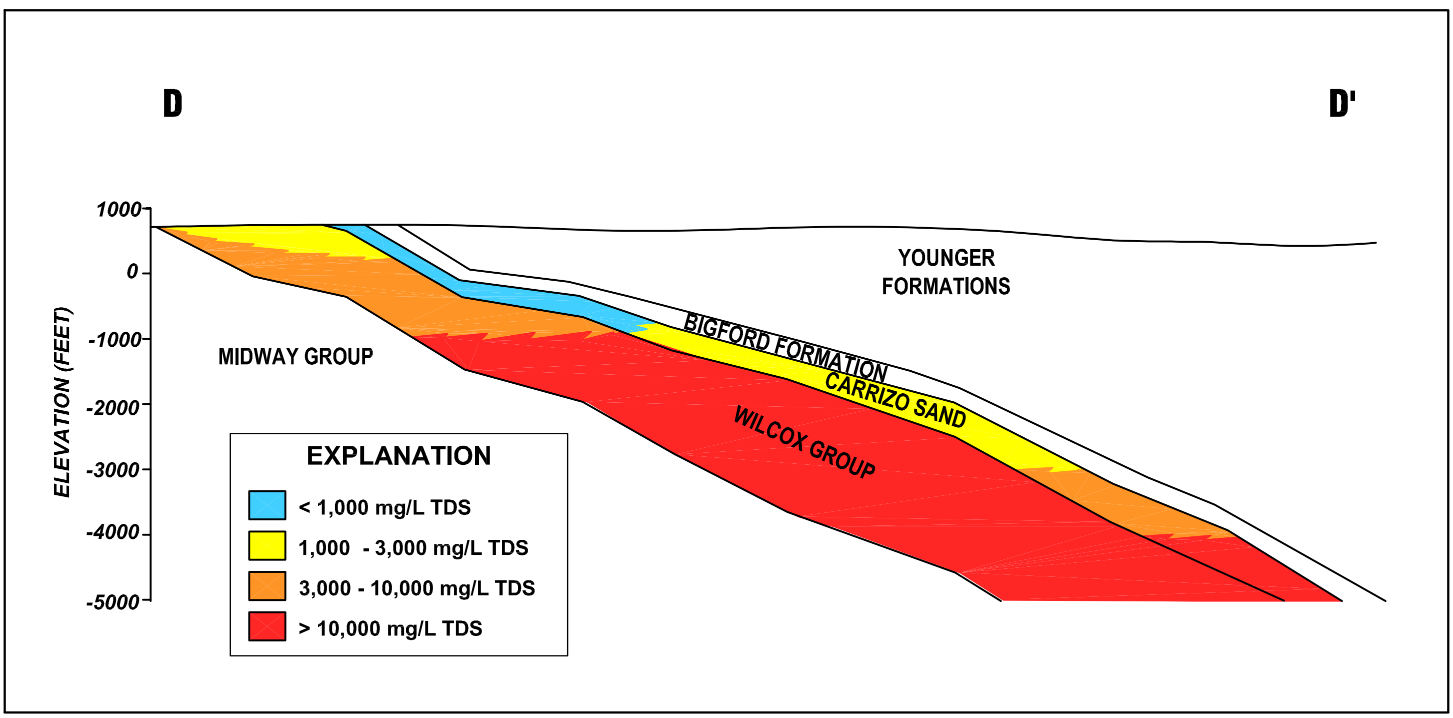
SIMPLIFIED CROSS SECTION B-B' OF THE CARRIZO-WILCOX AQUIFER WITH GENERALIZED WATER QUALITY RANGES
(Modified from Baker, 1995)

FIGURE 22



SIMPLIFIED CROSS SECTION C-C' OF THE CARRIZO-WILCOX AQUIFER WITH GENERALIZED WATER QUALITY RANGES
(Modified from Baker, 1995)

FIGURE 23



SIMPLIFIED CROSS SECTION D-D' OF THE CARRIZO-WILCOX AQUIFER WITH GENERALIZED WATER QUALITY RANGES
(Modified from Baker, 1995)

FIGURE 24

3.1.9 Gulf Coast

The Gulf Coast aquifer system consists of individual Tertiary and Quaternary age aquifers, which form a wide belt parallel to the Gulf Coast from Florida to Mexico. In Texas, the aquifer is found in all or parts of 54 counties, as shown in Figure 25, and is one of the most productive and heavily used aquifers in the state. Groundwater produced from the Gulf Coast aquifer system is almost entirely used for municipal, irrigation, and industrial purposes. The City of Houston is the largest single producer of groundwater from the aquifer system. Years of heavy pumpage in portions of the aquifer have resulted in areas of significant water-level decline, with declines of 200 to 300 feet having been measured in the greater Houston area.

The Gulf Coast aquifer system is composed of four individual aquifers, including, from shallowest to deepest, the Chicot, Evangeline, Jasper, and Catahoula aquifers. These aquifers consist of interbedded clays, silts, sands, and gravels, which are hydrologically connected to form the entire aquifer system. The maximum total sand thickness for the Gulf Coast aquifer system ranges from about 700 feet in the southern portion of the aquifer to 1,300 feet in the northern extent. Four schematic cross sections of the Gulf Coast aquifer system are shown in Figures 26 to 29. Each of these aquifers consists of several hydrostratigraphic units that vary hydrogeologically across the state. Not all of these aquifers are present throughout the system and nomenclature used to describe them often differs from one end of the system to the other.

The four aquifers that are considered part of the Gulf Coast aquifer system produce different amounts of groundwater. The Chicot and Evangeline are the most prolific aquifers in the system, followed by the Jasper. The Catahoula is a very minor producer of groundwater. In general, the Gulf Coast aquifer system is much more prolific in the east than in the southwestern area. Aquifer transmissivities in the northeastern region range from approximately 100,000 to 200,000 gpd/ft, and storage coefficients range from 3×10^{-3} in the down-dip confined areas to 0.01 near the outcrop. In the central Coastal Bend area aquifer transmissivities decrease to 35,000 to 70,000 gpd/ft, and in the Rio Grande Valley transmissivities decrease to 20,000 to 40,000 gpd/ft. The Catahoula Formation is generally not considered water-bearing in the southern third of the region. Storage coefficients remain the same throughout the region. Wells in much of the Gulf Coast aquifer system can easily produce between 1,000 and 3,000 gpm. Although these aquifer properties are for the fresh water portions of the aquifer system, transmissivities and storage coefficients are not expect to decrease significantly in the slightly- to moderately-saline portions of the aquifer system.

Recharge to the Gulf Coast aquifer system occurs through the infiltration of precipitation on the aquifer outcrop areas. Historically, discharge was through leakage into overlying units, however, currently most discharge is to wells producing from the aquifer. Groundwater flow is generally from the up-dip outcrop areas to down-dip areas.

Water quality varies with depth and locality in the Gulf Coast aquifer. As shown in Figure 25, the water quality is generally fresh in the northeastern half of the aquifer, from the Coastal Bend region to Louisiana. Some areas in this region do produce slightly-saline water, in particular near the coast between the City of Houston and

Louisiana. The groundwater quality in the southwestern half of the aquifer (generally south of the San Antonio River) is generally more brackish than in the northern section, with most areas containing slightly- to moderately-saline groundwater, and very few areas containing fresh water. As shown in the four cross sections (Figures 26 to 29), the depths that fresh, slightly-saline, moderately-saline, and saline groundwater is found varies from individual aquifer to aquifer throughout the extent of the aquifer system.

Summary

The Gulf Coast aquifer system may be an excellent source of brackish groundwater in many areas. The southwestern portion of the aquifer system is the best brackish groundwater resource because of the dominance of high TDS groundwater. The City of Brownsville is currently developing pilot projects to treat brackish groundwater by desalination for use as a public water supply. In addition, the aquifer system may be an excellent brackish groundwater resource in other areas, in particular in several areas at or near the coast where poor quality water is common. One notable location is along the coast between the City of Houston and Louisiana.

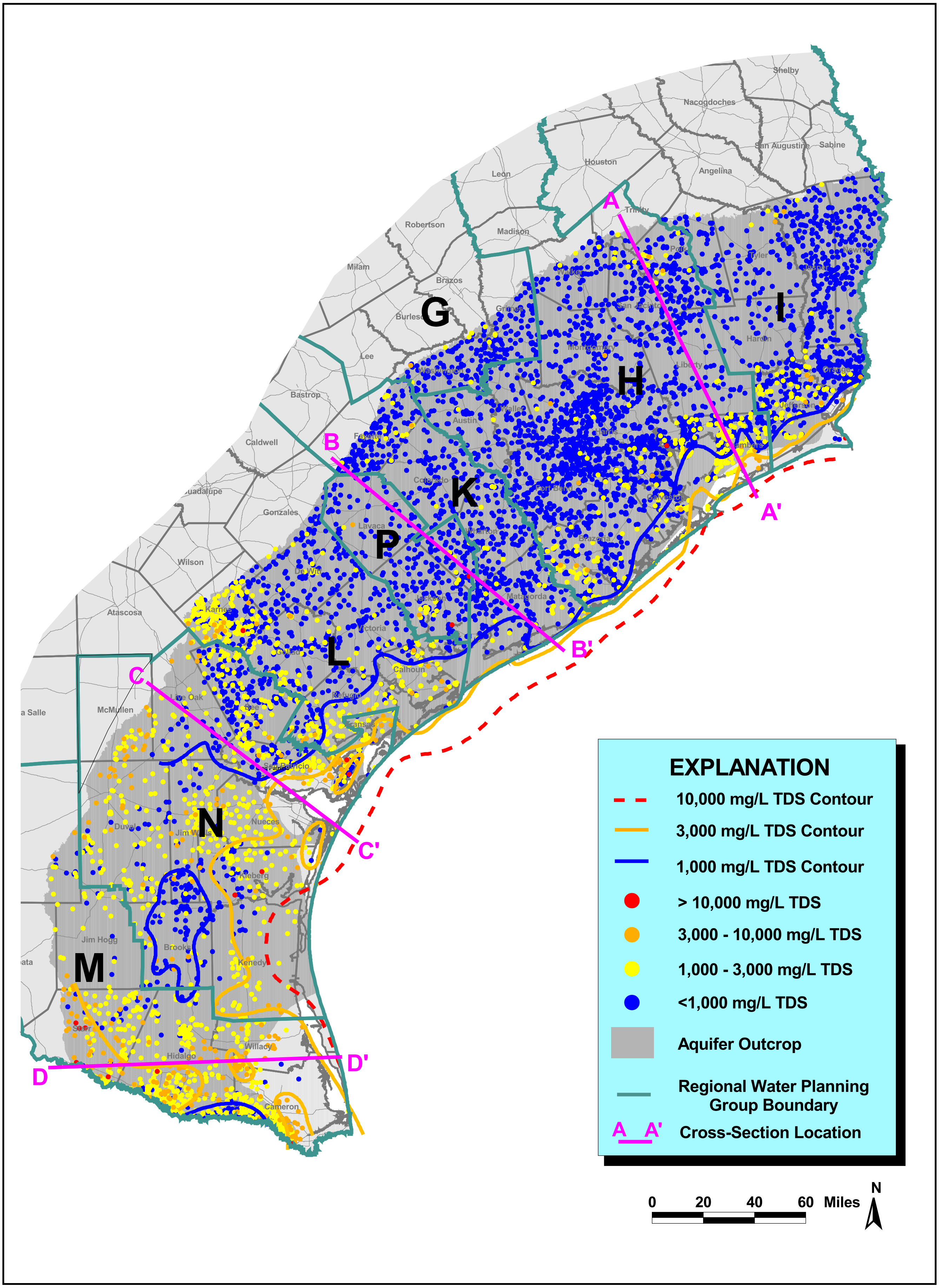
An important consideration in production of brackish groundwater from the Gulf Coast aquifer system is that the high production of brackish groundwater may cause subsidence. This is a concern in the coastal regions and will be an issue that should be addressed before brackish groundwater resources are considered in these areas.

Availability- MODERATE to HIGH- Except in Region P, where none of the brackish, down-dip extent of the Gulf Coast aquifer system is found, the availability of brackish groundwater from the aquifer is moderate to high. In East Texas, in particular between the City of Houston and the Louisiana border along the coast, a significant amount of brackish groundwater appears to be available. In these areas the aquifer is highly productive, leading to good availability. In the central and southern parts of the coast, the aquifer begins to become significantly less productive, and even though the area where brackish water is found increases, the availability is only considered average due to the decreased productivity.

Productivity- MODERATE to HIGH- In areas where brackish groundwater is available in East Texas, the Gulf Coast aquifer system is expected to have moderate to high productivity. In the central and southern portions of the coast, the aquifer decreases in productivity.

Source Water Production Cost- LOW to MODERATE- If brackish groundwater is available for use, the production of this water from the Gulf Coast aquifer system should be low to moderate. In East Texas, the aquifer is more productive but the brackish resources are generally found down-dip at greater depths. In the central and southern portions of the coast, the aquifer becomes significantly less productive but brackish water is found at shallower depths. In the southern third of the extent of the aquifer, nearly all groundwater in and near the outcrop is all brackish in quality.

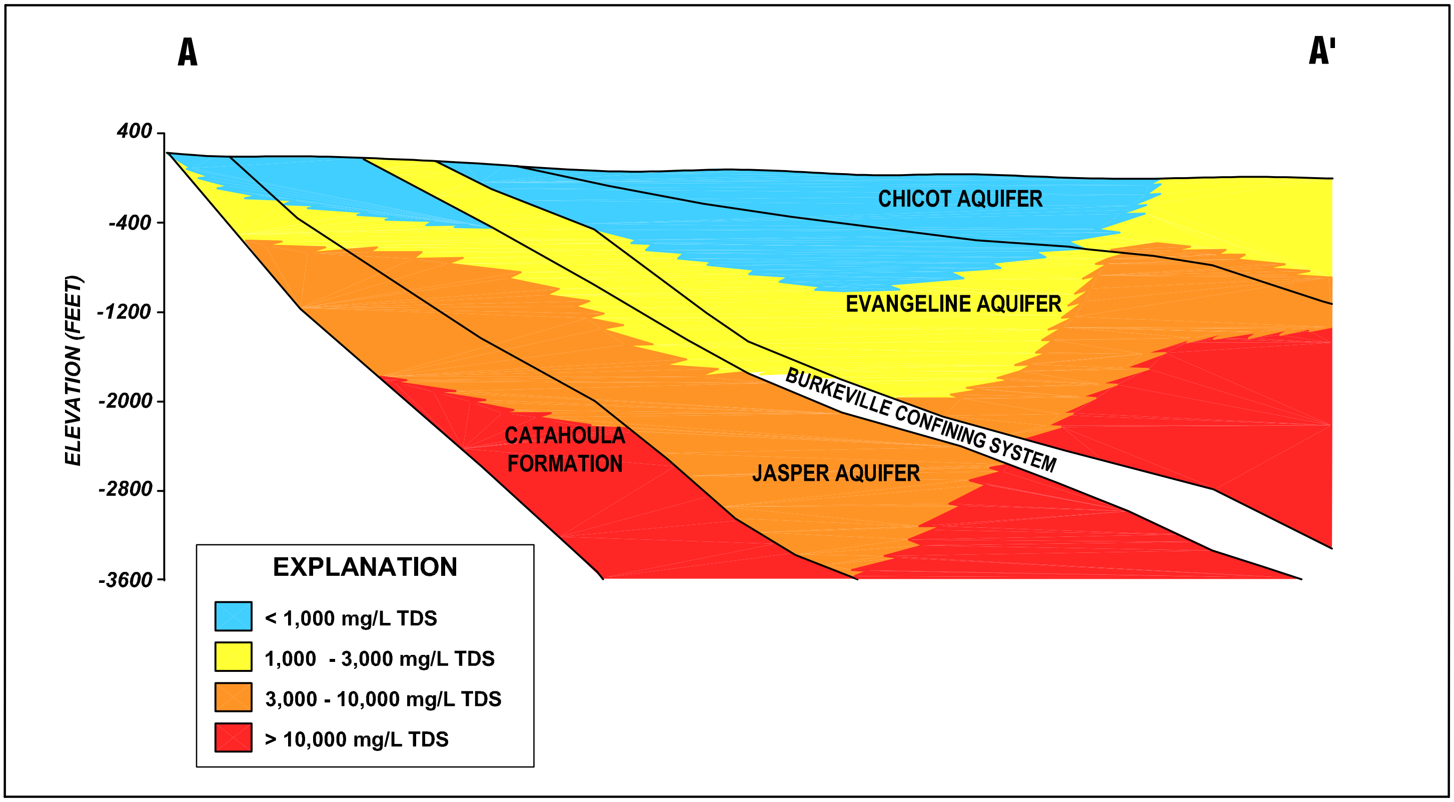
Summary of Brackish Water In the Gulf Coast Aquifer System			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
H- Region H	High	High	Low to Moderate
I- East Texas	High	High	Low to Moderate
K- Lower Colorado	Moderate to High	High	Low to Moderate
L- South Central Texas	Moderate	High	Low
M- Rio Grande	Moderate	Moderate	Low to Moderate
N- Coastal Bend	Moderate	Moderate to High	Low
P- Lavaca	Low	High	Low



GROUNDWATER QUALITY IN THE GULF COAST AQUIFER SYSTEM

FIGURE 25

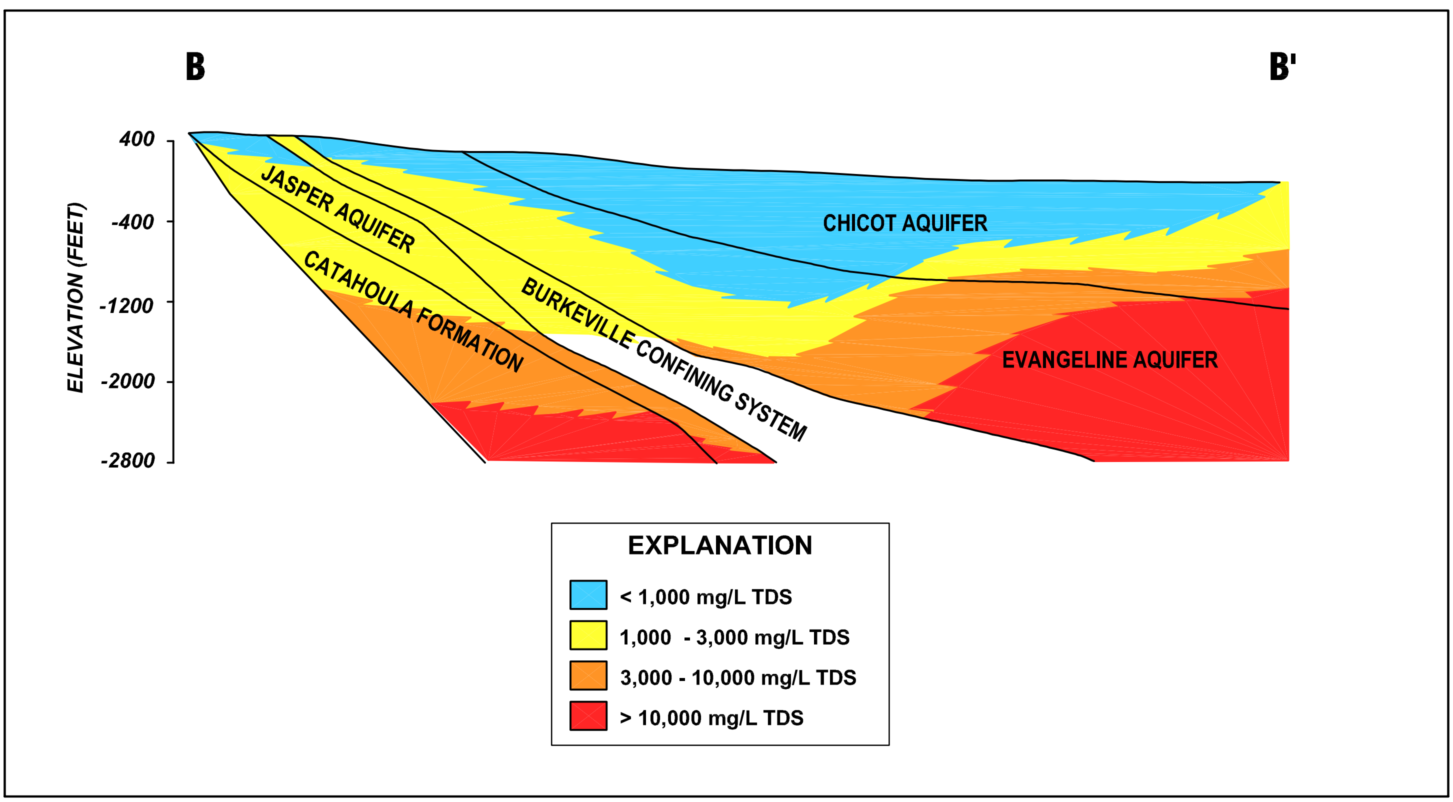
LBG-GUYTON ASSOCIATES



SIMPLIFIED CROSS SECTION A-A' OF THE GULF COAST AQUIFER SYSTEM WITH GENERALIZED WATER QUALITY RANGES

(Modified from Baker, 1979)

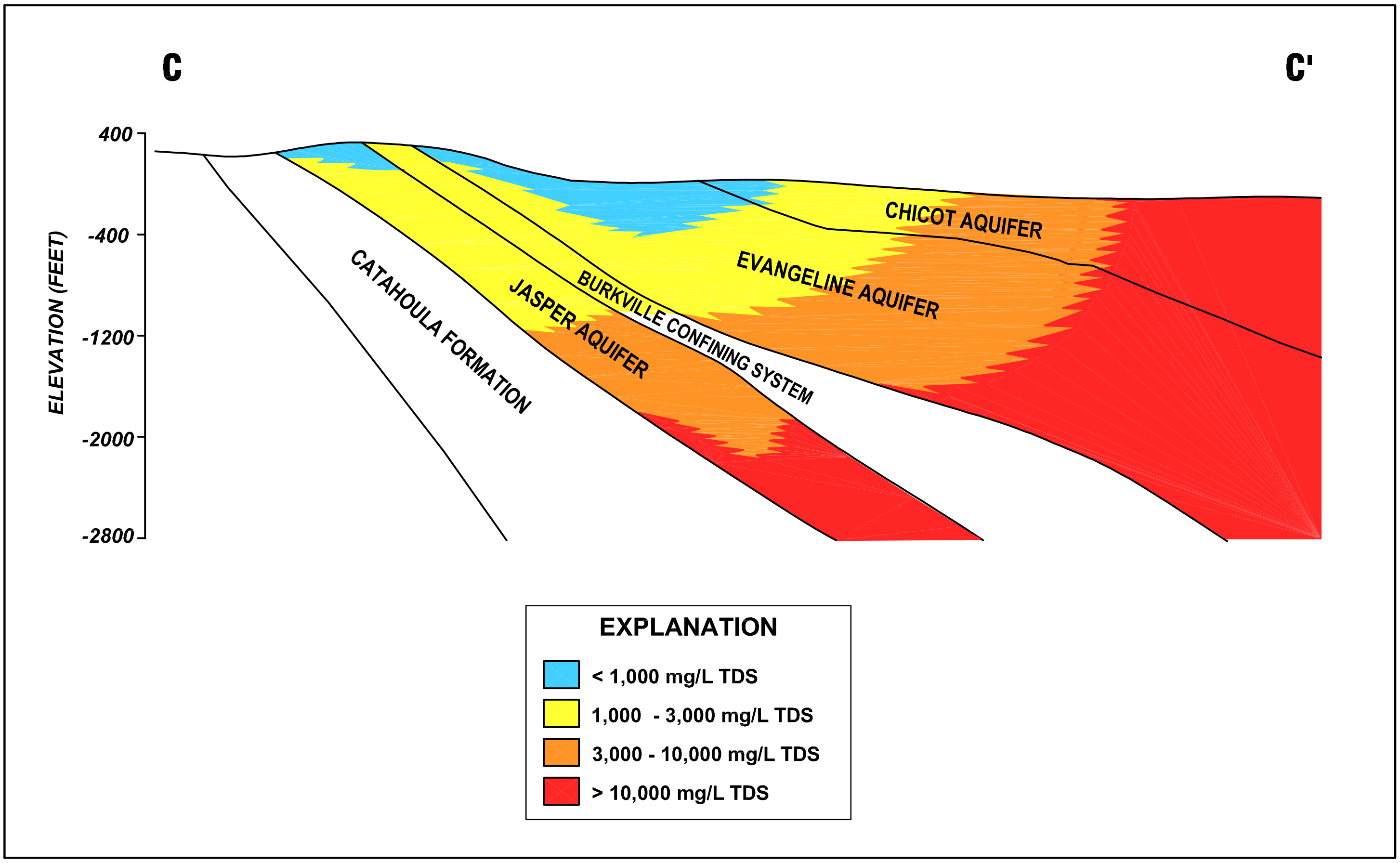
FIGURE 26



SIMPLIFIED CROSS SECTION B-B' OF THE GULF COAST AQUIFER SYSTEM WITH GENERALIZED WATER QUALITY RANGES

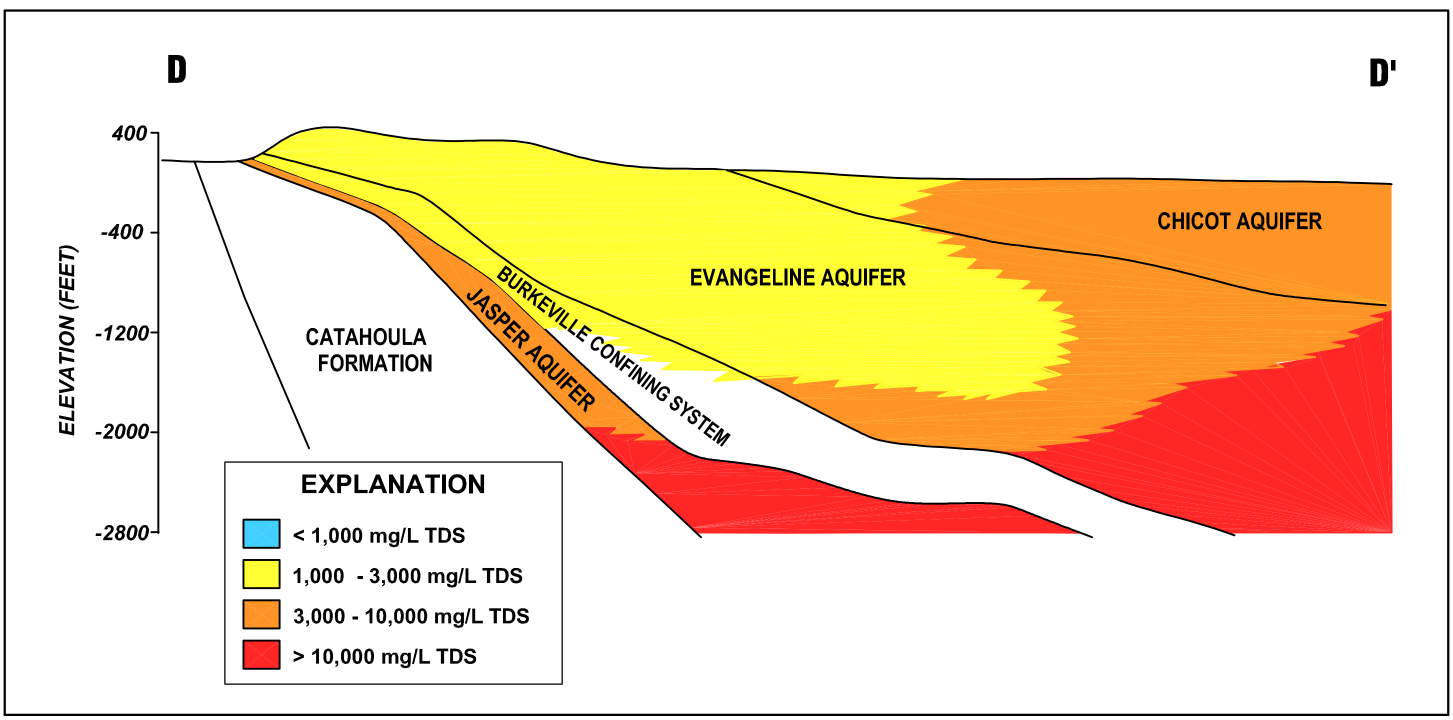
(Modified from Baker, 1979)

FIGURE 27



SIMPLIFIED CROSS SECTION C-C' OF THE GULF COAST AQUIFER SYSTEM WITH GENERALIZED WATER QUALITY RANGES
(Modified from Baker, 1979)

FIGURE 28



SIMPLIFIED CROSS SECTION D-D' OF THE GULF COAST AQUIFER SYSTEM WITH GENERALIZED WATER QUALITY RANGES
(Modified from Baker, 1979)

FIGURE 29

3.2 Minor and Other Aquifer Systems

3.2.1 Bone Spring-Victorio Peak

The Bone Spring-Victorio Peak aquifer is a Permian-age limestone aquifer that is located in northeastern Hudspeth County, as shown in Figure 30. This aquifer produces groundwater principally for irrigation in a region locally referred to as Dell Valley on the Texas side of the state border and Crow Flat in New Mexico.

A generalized cross section of the aquifer is shown in Figure 31. Groundwater occurs in limestone and dolomite formations of the Bone Spring-Victorio Peak throughout the Diablo Plateau region both in Texas and New Mexico. However, unlike elsewhere on the Diablo Plateau, the aquifer in the Dell Valley and Crow Flat area has been developed because of the relatively shallow water table and the presence of soils good for cultivation. Groundwater in the aquifer is concentrated in solution cavities that have developed along joints, fractures, and bedding planes, and these water-bearing zones have been found in wells drilled in excess of 2,000 feet. However, well production depends on the number and size of cavities intercepted by the well bore. While the aquifer is highly transmissive on a regional basis, locally well yields can vary significantly. Highly productive wells, which can produce up to 3,000 gpm, are those that intersect numerous solution cavities. However, a large number of lower capacity wells have been drilled in the vicinity of highly productive wells. Measured specific capacities range from 5 to over 60 gpm/ft of drawdown. Average annual recharge to the aquifer has been estimated to range from 90,000 to 100,000 acre-feet.

The relatively low hydraulic gradient of the water table results in an increase in depth to water to the west as the land surface altitude increases. Depth to water ranges from a few feet below the surface in the salt flats to more than 800 feet in higher elevations of the Diablo Plateau. Within the irrigated region of the valley, depths to water range from less than 50 feet along the eastern side to greater than 300 feet on the west. Transmissivities in cavernous zones in the aquifer range from 75,000 to more than 200,000 gpd/ft. Confined storage coefficients for this type of aquifer range from 1×10^{-3} to 1×10^{-4}.

The quality of groundwater underlying Dell Valley is generally brackish, very hard, and dominated by high levels of calcium, sodium, sulfate, and chloride. Water in the Dell Valley area can be classified as slightly- to moderately-saline, with TDS of most of the aquifer water ranging from approximately 1,000 to more than 6,000 mg/L and averaging about 3,500 mg/L. TDS is greatest along an area east to southeast of Dell City where concentrations range from 5,000 to 6,500 mg/L. Sulfate is the most prominent dissolved constituent in water from the aquifer, with concentrations typically ranging from approximately 600 to over 2,000 mg/1. Concentrations of calcium, sodium, and chloride are also high. A deterioration of water quality over time, especially in regards to sulfate and nitrate, suggests that some of the water historically pumped from the aquifer for irrigation use is returning to the aquifer.

Summary

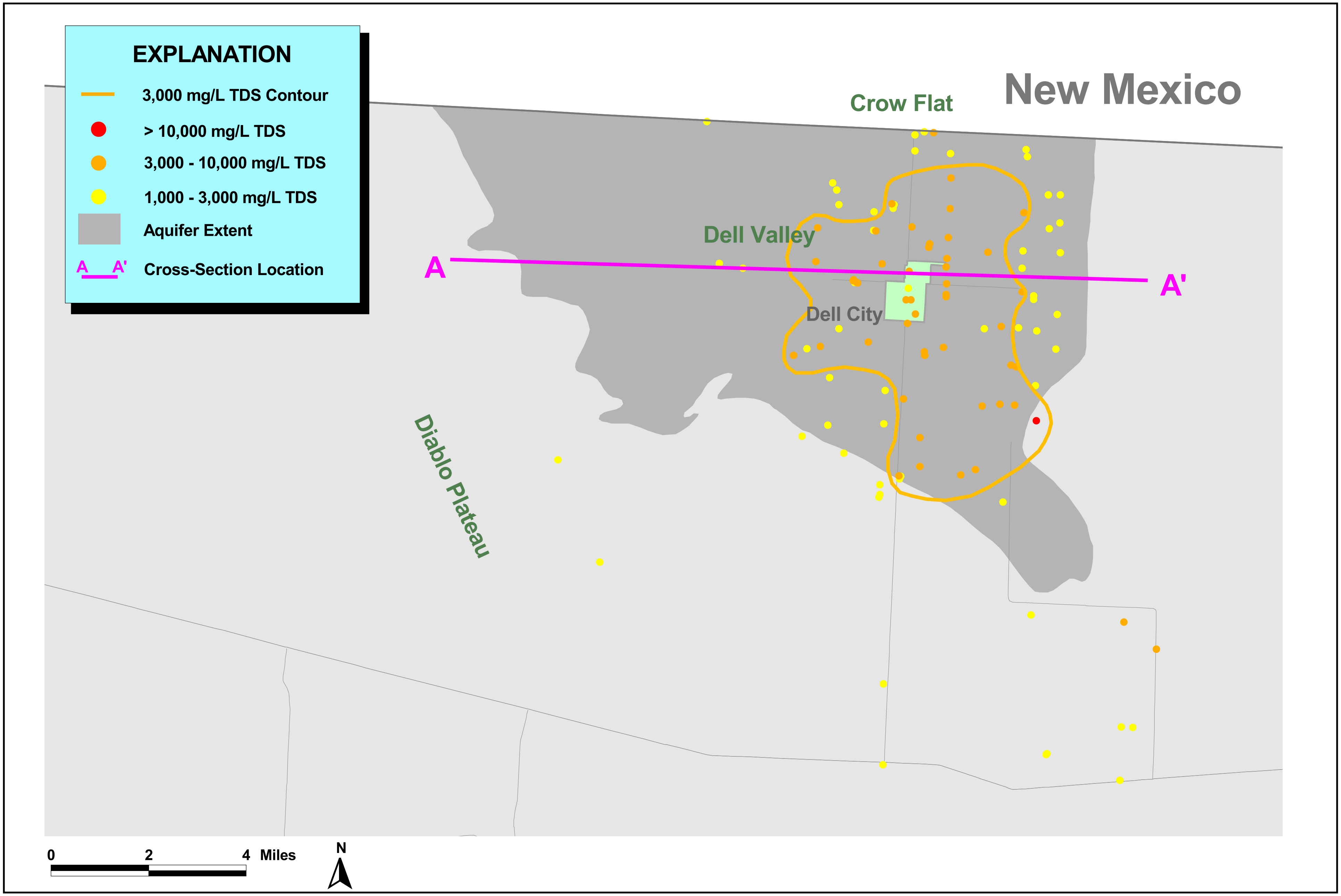
Most of the groundwater in the Bone Spring/Victorio Peak aquifer ranges from 1,000 to greater than 6,000 mg/L TDS. Because of this, and the shallow water table and relatively high recharge rate, the entire extent of the Bone Spring/Victorio Peak aquifer may be an excellent source of brackish water.

Availability- HIGH- Virtually the entire extent of this aquifer contains brackish groundwater with a high recharge rate.

Productivity- HIGH- Although well yields depend on the nature and extent of solution cavities encountered by the well, fairly high-capacity wells may easily be installed.

Source Water Production Cost- LOW to MODERATE- Because the water table is relatively shallow in this area, and high capacity wells can be installed in the aquifer, the relative production cost is expected to be low to moderate for this aquifer.

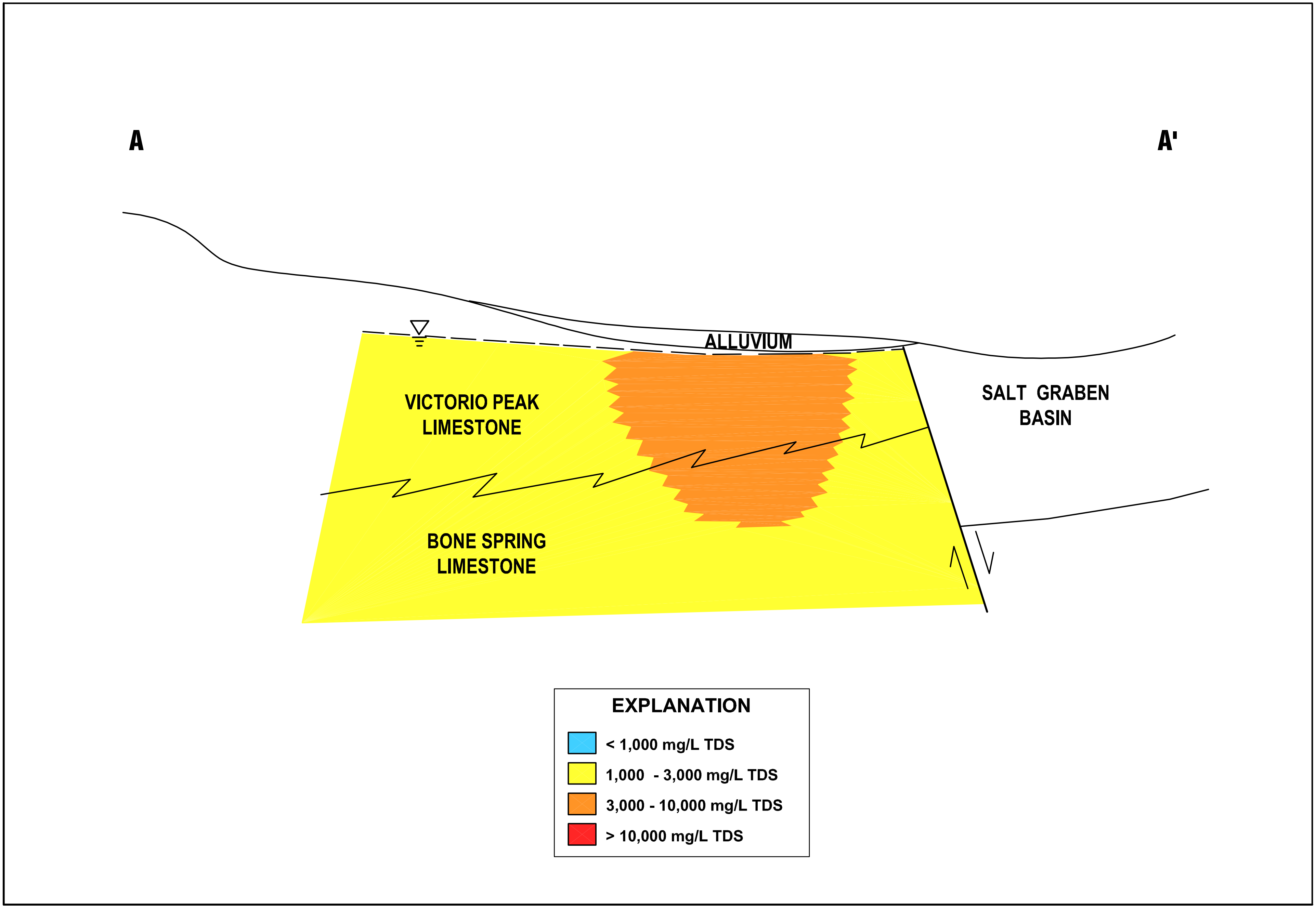
Summary of Brackish Water In the Bone Spring/Victorio Peak Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
E- Far West Texas	High	High	Low to Moderate



GROUNDWATER QUALITY IN THE
BONE SPRING-VICTORIO PEAK AQUIFER

FIGURE 30

LBG-GUYTON ASSOCIATES



SIMPLIFIED CROSS SECTION OF THE BONE SPRING-VICTORIO PEAK AQUIFER WITH GENERALIZED WATER QUALITY RANGES

(Modified from Ashworth, 1995)

FIGURE 31

LBG-GUYTON ASSOCIATES

3.2.2 Igneous

The Igneous aquifer system is located in West Texas, principally in Brewster, Presidio, and Jeff Davis Counties, as shown in Figure 32. The aquifer system is actually a series of distinct water-bearing units, all occurring in Tertiary-aged volcanic rocks. The groundwater occurs in fissures, fractures, and horizontal bedding planes of these volcanic rocks. Water from the Igneous aquifer system is used for irrigation, domestic and livestock, and municipal purposes, and is the sole source of water for the cities of Fort Davis, Alpine, and Marfa.

The volcanic rocks that comprise the Igneous aquifer system can be as thick as 6,000 feet, with an average thickness of about 1,000 feet. Over 40 identified formations make up the very complex Igneous aquifer system. The volcanic rocks are mainly composed of ash-flow tuffs, which are thin and fairly widespread, and lava flows, which are thicker and more areally extensive. Some of the individual formations may consist of multiple flows. These volcanic units are generally highly fractured and faulted.

The hydrogeology of the Igneous aquifer system is very complex, mainly due to the highly variable nature of the numerous individual water-bearing units that make up the aquifer system. Groundwater is found anywhere between 10 to more than 600 feet below the surface, and water levels can vary significantly, even between wells that are located fairly close together. Groundwater flow is generally from areas higher in the mountains to low lying areas at the base of the mountains. Well yields can vary from small to large, depending on the area where a well is located and the quantity and size of the fractures encountered by the well bore. Transmissivities in the Igneous Aquifer are highly variable due to the fractured nature of the aquifer, ranging from less than 200 to 13,000 gpd/ft. Storage coefficients are approximately 1×10^{-4} and unconfined specific yields are probably 0.01 to 0.02.

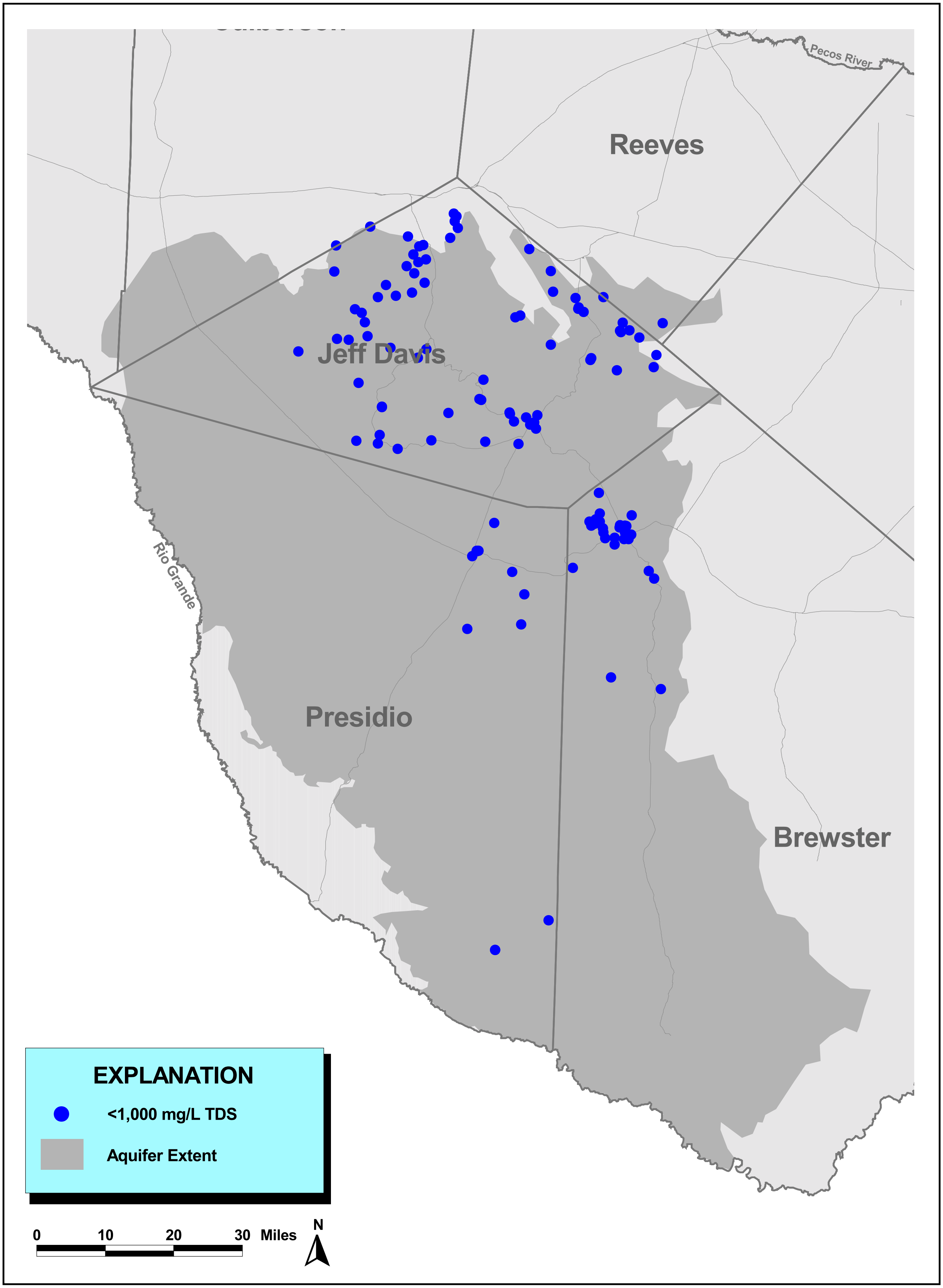
Recharge to the aquifer system is from the infiltration of precipitation, while discharge is to wells and more than 150 springs in the area, which have highly variable flows. Water quality is very good, with low TDS, indicating a fairly rapid recharge rate and flow through the aquifer. Because of this, there appears to be little or no brackish water available in the Igneous aquifer system.

Summary

Because of the rapid recharge and relatively insoluble nature of the Igneous rock formation materials, little or no brackish water is present in the aquifer.

Availability- NONE- No brackish water appears to be available from the Igneous aquifer system.

Summary of Brackish Water In the Igneous Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
E- Far West Texas	None	--	--



GROUNDWATER QUALITY IN THE IGNEOUS AQUIFER SYSTEM

FIGURE 32

LBG-GUYTON ASSOCIATES

3.2.3 West Texas Bolsons

The West Texas Bolsons are a series of fault-bounded, Quaternary age, basin-fill aquifers in the Trans Pecos region of Texas located in Culberson, Hudspeth, Jeff Davis, and Presidio Counties, as shown in Figure 33. These aquifers are part of the Basin-and-Range physiographic province, which is characterized by alternating structurally uplifted mountains and structurally downthrown basins. There are several distinct bolsons that make up the West Texas Bolsons, including Red Light Draw, Green River Valley, Presidio-Redford, Eagle Flat, and the Salt Basin, which is subdivided into Salt Flat, Wild Horse Flat, Michigan Flat, Lobo Flat, and Ryan Flat. Each of these is indicated in Figure 33. Water from these bolson aquifers is currently used for irrigation, domestic, and livestock supply, as well as some municipal water supplies. The towns of Presidio, Sierra Blanca, Valentine, and Van Horn rely on these aquifers for all of their municipal water supplies.

The alluvial fill in these bolson aquifers is derived from the erosion of the mountain ranges that surround them, and so different bolsons are composed of different materials. A simplified cross section of a bolson aquifer is shown in Figure 34. Water quality in the bolsons depends in part on the type of materials that make up the aquifer. Many of the bolsons, including Ryan Flat, Lobo Flat, portions of Presidio-Redford, Red Light Draw, and Green River Valley, are composed of relatively insoluble volcanic material, and therefore water quality in them tends to be good, and little or no brackish water is available from them. Other bolsons, including portions of the Salt Basin, may be filled with material derived from the erosion of more soluble limestones and sandstones and therefore would contain water that tends to be poorer in water quality, containing higher total dissolved solids. In addition, deposits at the margins of these basins tend to be coarser grained, and tend to contain fresher water than the finer grained deposits found in the central parts of these basins.

Groundwater found in the bolson aquifers is mostly found under water-table conditions, with water levels as deep as several hundred feet in the middle of the basins. In some, groundwater may be found under semi-confined conditions towards the center of the basins, where the fine-grained sediments are typically found. The bolson aquifers are capable of yielding moderate to large quantities of groundwater to wells, with yields as high as 3,000 gpm being possible, although most wells produce less than 1,000 gpm. Very few aquifer tests have been conducted in the West Texas Bolsons aquifers, and therefore most estimates of aquifer hydraulic characteristics are based on specific capacity data. In general, transmissivity estimates range from 30,000 to 90,000 gpd/ft, specific yieldd between 0.06 and 0.15, and specific capacity estimates for wells of 5 to 50 gpm/ft. In areas with a significant amount of groundwater production, long-term declines in water levels have been observed. Lobo and Ryan Flats have had as much as 140 feet of declines over a 23-year period, with 50 or more feet of recovery occurring after pumpage was reduced.

Recharge to these bolson aquifers is typically limited, due mainly to the lack of precipitation that occurs in this region of the state. Recharge primarily occurs in the fractured rock formations that comprise the surrounding highlands and in the alluvial fans along the perimeter of the basins. In some areas there is groundwater flow interaction with the Rio Grande. Discharge from most of the bolson aquifers is to the Rio Grande (for Presidio-Redford, Green River Valley, and Red Light Draw). Groundwater in some of the bolsons may discharge via underflow to deeper units, and eventually to the Rio Grande.

Although, as indicated above, there are several individual bolsons that comprise the West Texas Bolsons, most do contain little or no brackish groundwater, including Red Light Draw, Green River Valley, Eagle Flat, Lobo Flat, and Ryan Flat. A more detailed description of the bolson aquifers that do contain brackish groundwater is given below.

<u>Salt Basin</u>- Brackish to saline groundwater occurs in the northern half of the Salt Basin, specifically in the Salt Flat, Wild Horse Flat, and Michigan Flat sub-basins. The Salt Flat portion of the Salt Basin is currently not classified by the TWDB as part of the West Texas Bolsons aquifer because groundwater produced from this area generally has total dissolved solids of greater than 3,000 mg/L. However, because this report focuses on brackish water potential in the state, this area has been added to the aquifer designation shown in Figure 33.

The Salt Flat is comprised mainly of lacustrine clays and sand up to 2,000 feet thick, and contains mainly saline water. Slightly-saline groundwater is generally found at the basin margins, and moderately-saline groundwater is found in the central parts of the basin, as shown in Figure 33.

Wild Horse and Michigan Flats are located in the north-central part of the Salt Basin, south of the Salt Flats. These basins consist of up to several thousand feet of coarse- to fine-grained material, generally containing more sand and gravel than the Salt Flats. As shown in Figure 33, groundwater in the northern portion of Wild Horse and Michigan Flats is similar to the Salt Flats, with fresh to slightly-saline water at the basin margins and moderately-saline water in the central part of the basin.

<u>Presidio-Redford</u>- The Presidio and Redford Bolsons (Presidio-Redford) are located in Presidio County adjacent to the Rio Grande. The Presidio Bolson is up to 5,000 feet thick with fine-grained basin fill. The Redford is much thinner, averaging only about 500 feet thick. Groundwater flow in these aquifers is away from the margins of the bolsons and towards the Rio Grande. Water quality in the coarser-grained portions of the aquifers is probably fresh, and in the finer-grained portions of the bolsons, located along the Rio Grande in the center of the basins, is probably moderately-saline or poorer.

Summary

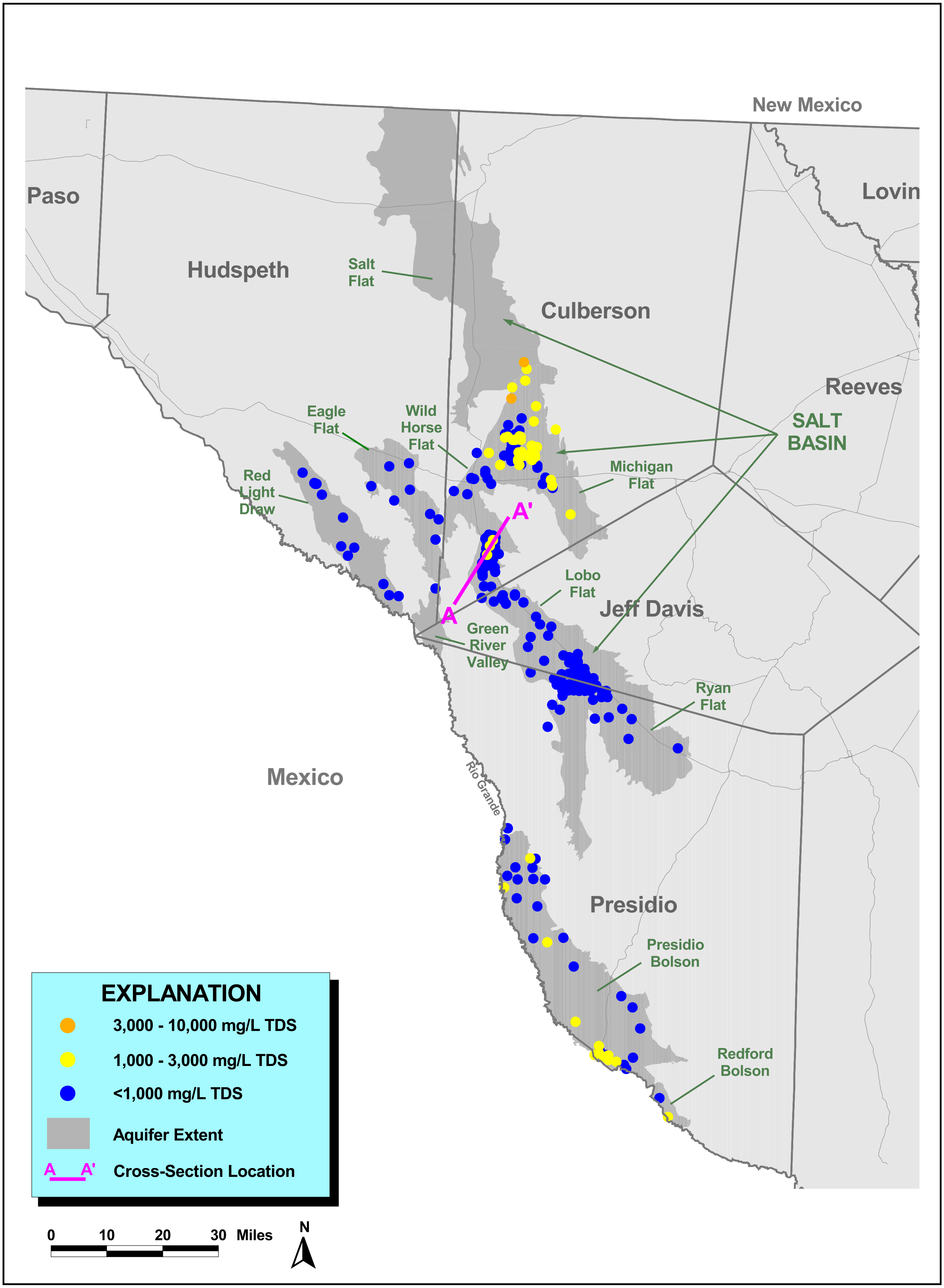
Most groundwater found in the West Texas Bolsons appears to be fresh. Some brackish water can be found in parts of the Presidio Bolson and in the northern part of the Salt Basin. Of these, the Salt Basin has the greatest potential for the production of brackish water. Groundwater is present in unconfined conditions, and so relatively large storage coefficients are typical.

<u>Availability</u>- MODERATE- Although in most of the West Texas Bolsons there is little to no brackish groundwater available, as described above, in areas where brackish groundwater is available, specifically in the Salt Basin, these aquifers may be a reasonably good source of brackish groundwater.

Productivity- MODERATE- Where available, brackish groundwater from the West Texas Bolsons aquifers should be relatively practicable to produce, and the aquifer is expected to have moderate productivity.

Source Water Production Cost- MODERATE- Low to average well yields from the brackish portions of these aquifers keep the relative cost of producing groundwater from the brackish sections moderate. Well depths may be shallow in some areas, but deeper in others.

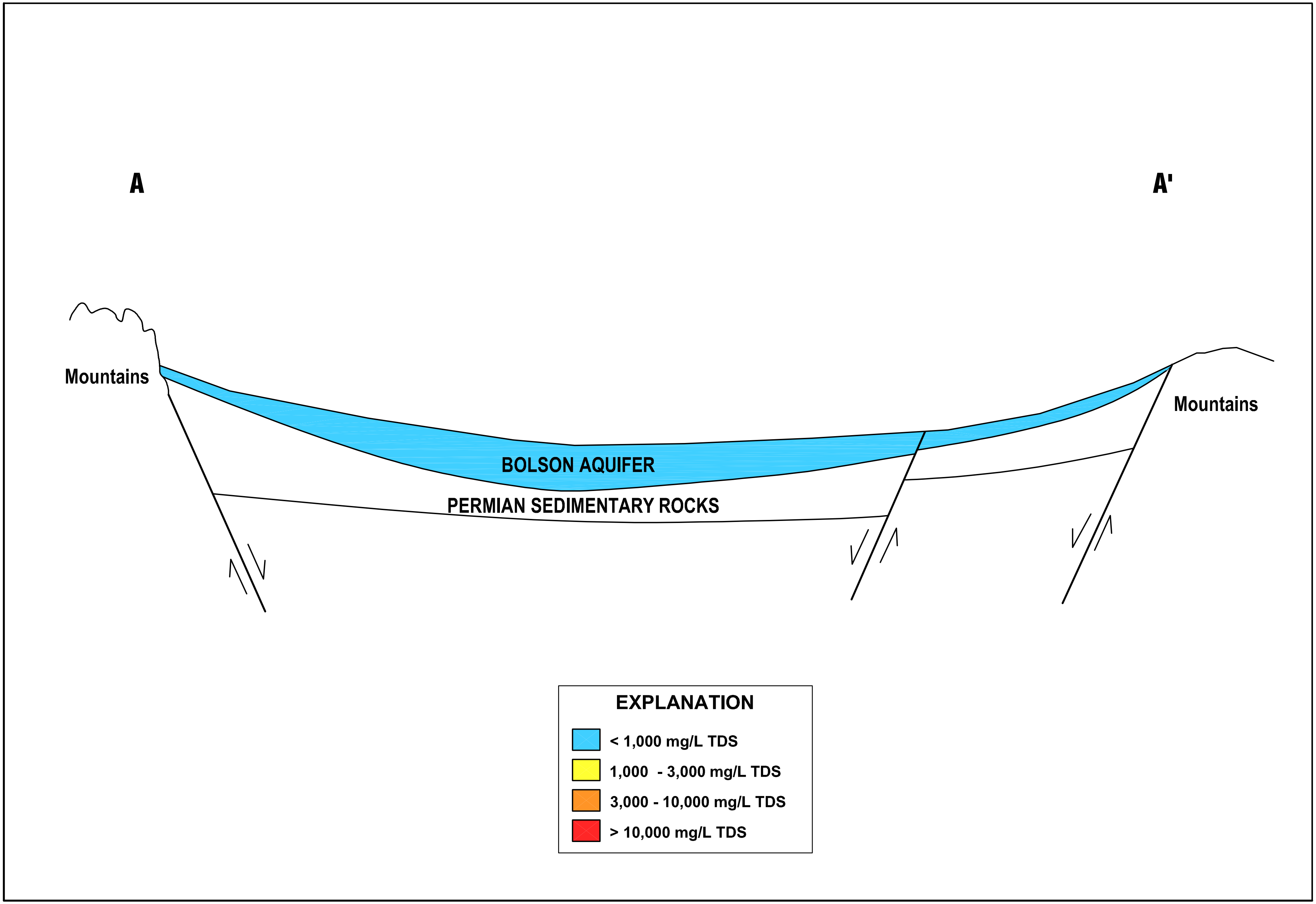
Summary of Brackish Water In the West Texas Bolsons Aquifers			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
E- Far West Texas	Moderate	Moderate	Moderate



GROUNDWATER QUALITY IN THE
WEST TEXAS BOLSONS AQUIFERS

FIGURE 33

LBG-GUYTON ASSOCIATES



SIMPLIFIED CROSS SECTION OF THE WEST TEXAS BOLSONS AQUIFERS WITH GENERALIZED WATER QUALITY RANGES
(Modified from Black, 1993)

FIGURE 34

LBG-GUYTON ASSOCIATES

3.2.4 Rustler

The Rustler is a Permian-age aquifer located in the Trans Pecos region of West Texas, mainly in Culberson, Reeves, Loving, Ward, and Pecos Counties, as shown in Figure 35. The formation occurs in the subsurface over a much larger area, however, water wells are primarily limited to the area depicted in Figure 35. Most of the outcrop area of the Rustler is located in eastern Culberson County, and extends eastward and southward in the subsurface from this outcrop area. Very few wells have been completed in the Rustler, resulting in very little data upon which to base an evaluation of the aquifer. Most of the wells that have been completed in the Rustler aquifer are used for irrigation, livestock, or secondary recovery operations in West Texas oil fields.

The Rustler Formation is primarily composed of dolomite and anhydrite, with a basal sand and conglomerate containing some shale. Small amounts of limestone and halite (salt) can also be found in the formation. The Rustler is generally between 200 and 500 feet thick throughout the region, as shown in the cross section in Figure 36. Most of the water produced from the Rustler is produced from dissolution cavities within the dolomite/anhydrite of the Upper Member of the formation.

Groundwater from the Rustler aquifer is not producible throughout the area, and where it is available, yields to wells can range from small to large, ranging from less than 10 to over 4,000 gpm. Groundwater in the Rustler aquifer is found under mostly confined conditions; in some cases flowing artesian wells have produced more than 1,000 gpm. Because so few wells have been completed into the Rustler, there are few data on the hydraulic characteristics of this aquifer, and insufficient water-level data to produce a reasonable water-level map. However, based on similar aquifers and historic water-level declines, overall transmissivities are probably less than 5,000 gpd/ft, and storage coefficients are probably between 1×10^{-4} and 1×10^{-5}.

Recharge to the Rustler occurs by the infiltration of precipitation and stream runoff on the outcrop, and by cross-formational flow from adjacent aquifers. The groundwater in the Rustler appears to be old, more typical of a slow moving groundwater flow system. This would indicate that most of the recharge is not from recent precipitation, but rather from cross-formational flow. Discharge from the Rustler is to the overlying Edwards-Trinity (Plateau) and Cenozoic Pecos Alluvium aquifers, to seeps and springs, and to wells. As much as 4,000 acre-feet/year is estimated to be available from the aquifer without depleting storage.

Rustler groundwater quality is generally poor, containing between 1,000 and 5,000 mg/L TDS. There does not appear to be any clear salinity pattern in the Rustler in the inferred direction of groundwater flow. In general, water produced from the Upper Member is slightly- to moderately-saline, and the basal beds contain greater than 10,000 mg/L TDS groundwater. The geochemistry of produced water shows that the groundwater is mainly a calcium-magnesium-sulfate type, which indicates the influence of anhydrite, dolomite, and halite dissolution.

Summary

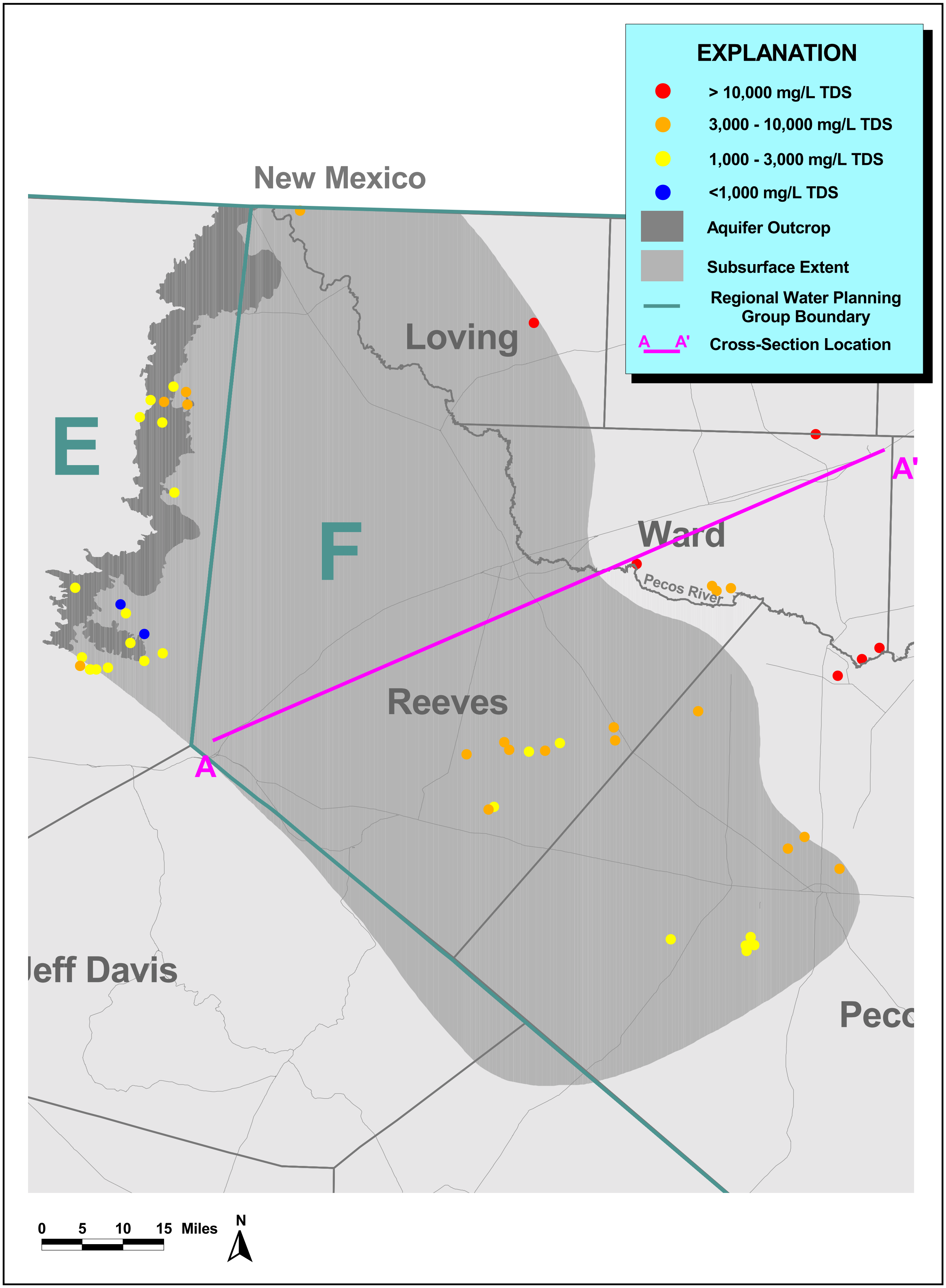
In general, the Rustler is a very understudied aquifer, and lacks sufficient data to make an accurate assessment of the groundwater resources contained in it. Based on the limited data that is available, it appears that slightly- to moderately-saline water occurs throughout most of the extent of the aquifer. However, because of the apparent random occurrence of high yielding wells, the exploration and development of brackish waters may be difficult.

Availability- LOW to HIGH- Most of the Rustler is found in Region F, where the availability of brackish groundwater appears to be high, based on the limited data available. However, low availability is expected in the Region E portion of the aquifer.

Productivity- LOW to HIGH- Because of the unpredictable nature of the Rustler, consistent well yields are not dependable, however the overall productivity of the Rustler is considered to range from low to high.

Source Water Production Cost- MODERATE to HIGH- As noted above, well yields in the Rustler vary widely, even over short distances. Depths to the water-producing zone over much of the aquifer's subsurface extent may be significant. This will result in moderate to high production costs.

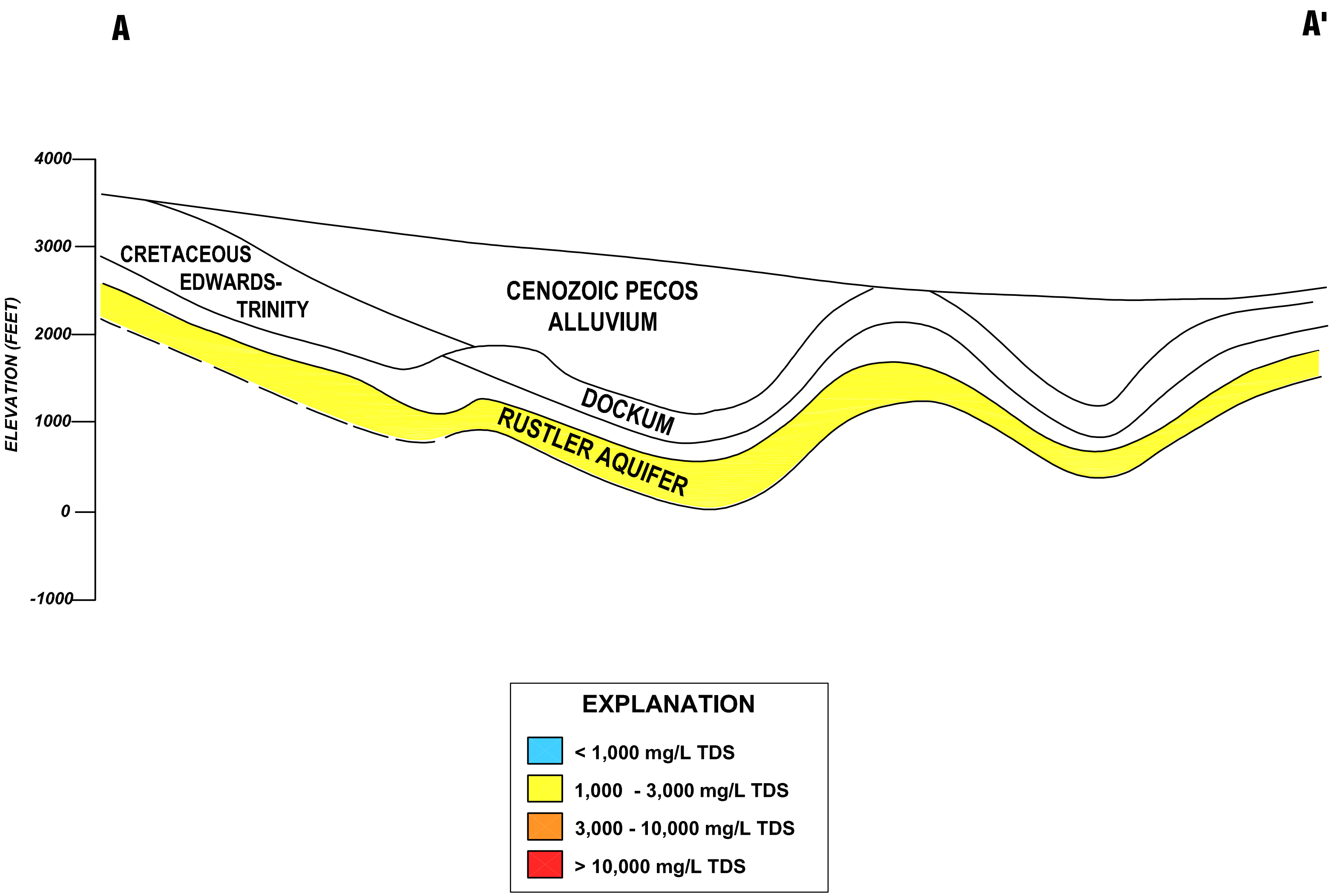
Summary of Brackish Water In the Rustler Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
E- Far West Texas	Low to Moderate	Low	Moderate
F- Region F	High	Low to High	Moderate to High



GROUNDWATER QUALITY
IN THE RUSTLER AQUIFER

FIGURE 35

LBG-GUYTON ASSOCIATES



SIMPLIFIED CROSS SECTION OF THE RUSTLER AQUIFER WITH GENERALIZED WATER QUALITY RANGES

(Modified from Ashworth, 1990)

FIGURE 36

LBG-GUYTON ASSOCIATES

3.2.5 Marathon

The Marathon aquifer is located in the Marathon Basin in Brewster County in West Texas, as shown in Figure 37. The aquifer is composed of a series of water-bearing formations, including the Marathon Limestone, which is the most productive formation in the area, as well as several other formations that yield lesser amounts of water to wells in the area. Most of the wells that produce from the aquifer are used for domestic and livestock purposes, with the exception of public supply wells in the town of Marathon.

While the Paleozoic rocks in the Marathon Basin are thousands of feet thick, most of the groundwater production in the area occurs at depths of less than 1,000 feet. The occurrence of groundwater is largely controlled by the geologic structure of the area. Most of the production is from the Marathon Limestone where upfolding has brought this formation to relatively shallow depths and the groundwater is under water-table conditions. Groundwater is produced from crevices, joints, and other cavities in the limestone. Where the Marathon Limestone is found at greater depths, the groundwater is more likely to occur under artesian (confined) conditions.

As with some other aquifers in this area of Texas, the Marathon aquifer has been penetrated by very few wells, and therefore there is a significant lack of data to evaluate the properties of the aquifer. No data exist on which to base aquifer hydraulic characteristics, nor to determine groundwater flow characteristics. Groundwater in the Marathon aquifer likely moves to the south and southeast toward the Rio Grande. Well yields range from 10 to 300 gallons per minute. The only wells producing significant quantities of water are producing from a fault zone in the City of Marathon. Based on well yields from wells producing from the Marathon aquifer and characteristics of similar aquifers, transmissivities may be less than 5,000 gpd/ft, with storage coefficients of 1×10^{-4} to 1×10^{-5}.

Recharge to the Marathon aquifer is from the infiltration of precipitation and stream runoff. Estimates of annual recharge are approximately 25,000 acre-feet/year[1]. Discharge from the aquifer is from springs, evapotranspiration, underflow toward the Rio Grande, and from pumpage. However, pumpage only accounts for 400 to 500 acre-feet/year of the total discharge, and discharge to springs is estimated at only about 1,000 acre-feet/year, meaning that much of the water in the aquifer is discharging through either underflow to other aquifers, or to evapotranspiration.

Most of the water produced from the Marathon aquifer is of good quality, with total dissolved solids generally less than 1,000 mg/L. No data exists to evaluate the existence of brackish water at deeper depths.

Summary

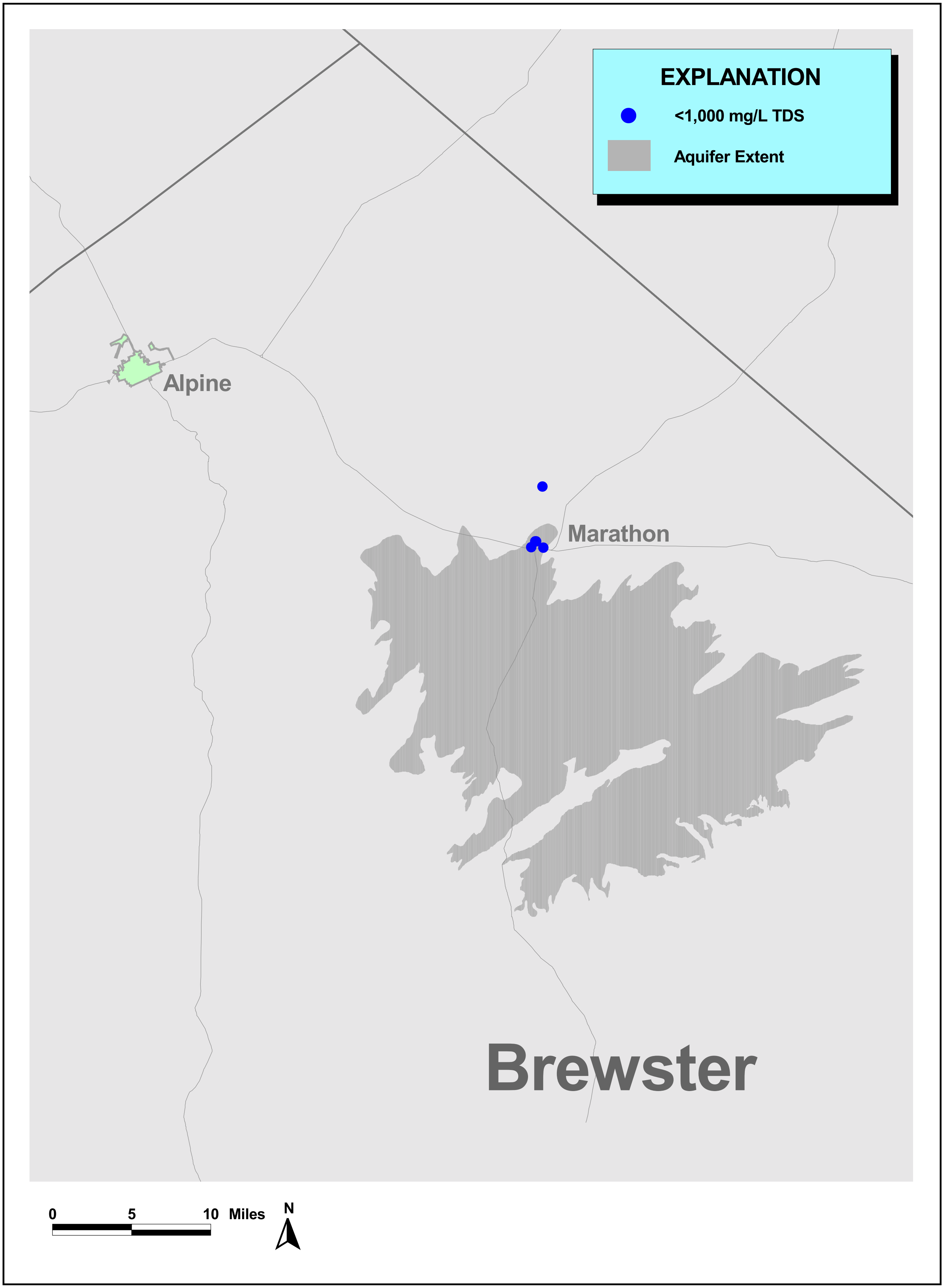
In summary, the Marathon aquifer is largely an unused aquifer in West Texas that may contain some slightly- to moderately-saline groundwater, especially in deeper sections. However, nearly all of the existing wells completed in this aquifer are in the shallower, fresh water sections, and no data exist to evaluate the potential for the existence of brackish water. The TWDB is currently conducting an update study on this aquifer.

Availability- UNKNOWN

Productivity- UNKNOWN

Source Water Production Cost- UNKNOWN

Summary of Brackish Water In the Marathon Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
E- Far West Texas	Unknown	Unknown	Unknown



GROUNDWATER QUALITY
IN THE MARATHON AQUIFER

FIGURE 37
LBG-GUYTON ASSOCIATES

3.2.6 Capitan Reef Complex

The Capitan is a Permian-age reef that parallels the western and eastern edges of the Delaware Basin in two strips 5 to 14 miles wide, as shown in Figure 38. It is exposed at land surface in the Guadalupe and Apache Mountains in Culberson County and the Glass Mountains in northern Brewster County. The aquifer associated with the various formations that comprise the reef is referred to as the Capitan Reef Complex aquifer. The aquifer extends northward into New Mexico where it provides abundant fresh water to the City of Carlsbad. Most of the groundwater pumped from the aquifer in Texas is used for oil reservoir water-flooding operations in Ward and Winkler Counties and agriculture irrigation in Pecos, Culberson, and Hudspeth Counties.

The Capitan is composed of 1,500 to 2,000 feet of massive, cavernous dolomite, limestone, and reef material. Well depths range from very shallow in the mountains to over 1,000 feet in the Diablo Farms area of northern Culberson and Hudspeth Counties, and to over 4,000 feet in Pecos, Ward, and Winkler Counties. Water in the Capitan aquifer is generally under artesian pressure. Due to the cavernous nature of this aquifer, well yields commonly range from a few hundred to more than 1,000 gpm. The aquifer in Texas has not been sufficiently studied and, therefore, data are lacking in some areas of the aquifer's extent. Transmissivities in the Capitan aquifer average approximately 40,000 gpd/ft, but may be as high as 120,000 gpd/ft. Storage coefficients are estimated to be about 1×10^{-3} to 1×10^{-4}.

The aquifer generally contains water of marginal quality, with most wells yielding water between 1,000 and 3,000 mg/L TDS. The freshest quality water is located near areas of recharge where the reef is exposed at the surface in the three mountain ranges. Capitan groundwater containing less than 3,000 mg/L (and in some cases, less than 1,000 mg/L) has been pumped for irrigation use in an area south of the Guadalupe Mountains in the Diablo Farms area of Culberson and Hudspeth Counties, and for livestock use in the Apache and Glass Mountains. Deeper wells in Pecos, Ward and Winkler Counties produce groundwater containing dissolved solids in excess of 3,000 mg/L. The highest concentrations occur in central Ward County and are in excess of 10,000 mg/L.

Summary

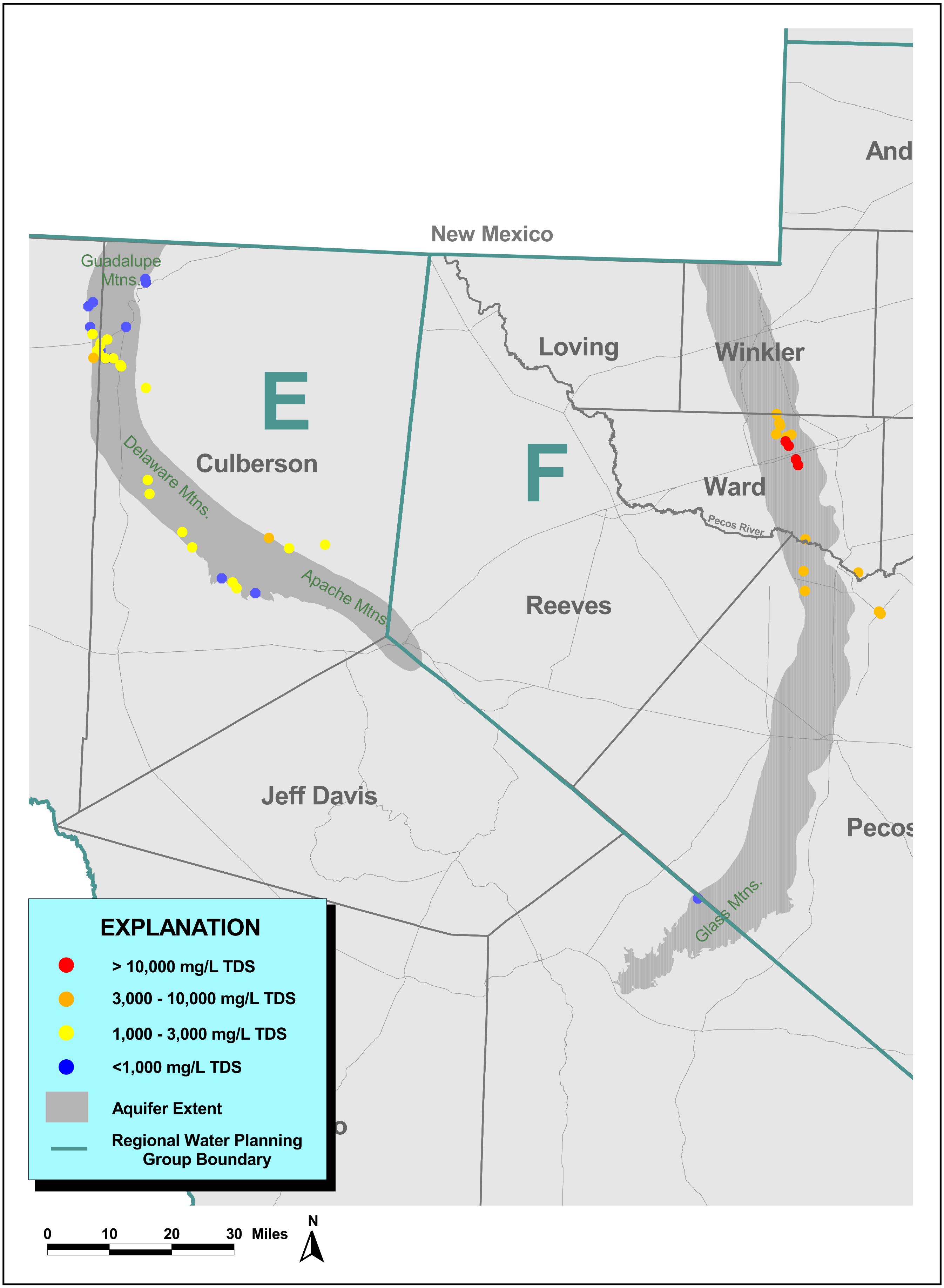
Groundwater in the Capitan Reef Complex aquifer is predominantly slightly- to moderately-saline. Other than its occurrence in the mountain ranges, the aquifer has the potential to produce very large quantities of groundwater to wells, and should be considered a very good potential brackish groundwater resource.

Availability- HIGH- Most of the extent of the Capitan Reef aquifer contains brackish groundwater. Because of this, and the very thick nature of the aquifer, availability is considered to be good.

Productivity- HIGH- Very large capacity wells can be completed in the Capitan Reef aquifer. Water levels are generally fairly high because of the artesian nature of the aquifer, resulting in a high productivity for this aquifer.

Source Water Production Cost- MODERATE- Although wells may be deep in the Capitan Reef aquifer, very high capacity wells can be installed. This results in a moderate relative cost for producing from the aquifer.

Summary of Brackish Water In the Capitan Reef Complex Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
E- Far West Texas	High	High	Moderate
F- Region F	High	High	Moderate



GROUNDWATER QUALITY IN THE CAPITAN REEF AQUIFER

FIGURE 38

LBG-GUYTON ASSOCIATES

3.2.7 Dockum

The Dockum aquifer is a Triassic age sandy to silty aquifer that occurs in all or parts of 44 counties from the Texas Panhandle to the northern part of the Trans Pecos region, as shown in Figure 39. Fresh to brackish groundwater from the Dockum is used for irrigation, public water supplies, and for oil field secondary recovery operations. Municipal users of Dockum groundwater include the cities of Sweetwater, Snyder, Pecos, Colorado City, and Kermit.

The Dockum Group consists of up to 2,000 feet of sands, silts, shales, and some gravels deposited in ancient structural Permian basins. A simplified cross section of the Dockum aquifer is shown in Figure 40. The Dockum Group is comprised of several units, including the Chinle, Santa Rosa, Trujilo, and Tecovas Formations. The primary water-bearing zone in the Dockum Group is the Santa Rosa Formation, which consists of up to 700 feet of sand, silt, and conglomerate, with some layers of shale. Additional discontinuous sandstone lenses occur elsewhere within the Dockum that also produce water, but in less quantity. Individual sandstone beds become progressively thinner, finer grained, and less water productive toward the center of the basin.

Except in the outcrop area, water in the Dockum aquifer is found under confined conditions. Where the "Santa Rosa" sand occurs close to outcrop, the aquifer is hydrologically continuous with overlying, water-bearing formations, including the Ogallala, Cenozoic Pecos Alluvium, and Edwards-Trinity (Plateau). Groundwater flow in the Dockum is to the east and southeast, and locally to the Canadian River. Well yields from the Dockum aquifer vary widely, ranging up to 2,500 gpm. However, because the permeability of the Dockum is typically low due to the fine-grained nature of the formation, most yields are between 100 and 400 gpm. Transmissivities in the Dockum range from less than 500 gpd/ft to more than 35,000 gpd/ft. Storage coefficients range from 4×10^{-4} to 4×10^{-5}. Specific capacities range from less than one to nearly 40.

Recharge to the Dockum is from precipitation on the outcrop in the eastern and southern edges of the aquifer, and from leakage from both overlying and underlying formations. Annual recharge has been estimated to be approximately 31,000 acre-feet[1]. Discharge from the aquifer is to wells, to small springs and streams in the Canadian River basin, and through cross-formational leakage to overlying and underlying aquifers. Most discharge currently is to wells.

Water quality from groundwater in the Dockum is variable, but as shown in Figure 39, it is generally poor. TDS concentrations can exceed 60,000 mg/L in the center of the Midland Basin, and most of the aquifer within Texas contains brackish water. Fresh groundwater can be found in the Dockum at the margins of the aquifer, including near the Canadian River, along the eastern outcrop, and in the southwestern part of the aquifer. Higher TDS groundwater is found in much of the rest of the aquifer extent. Fresh groundwater from the Dockum that is currently being used for municipal supply often contains chloride, sulfate, and dissolved solids that are near or exceed safe drinking-water standards.

Summary

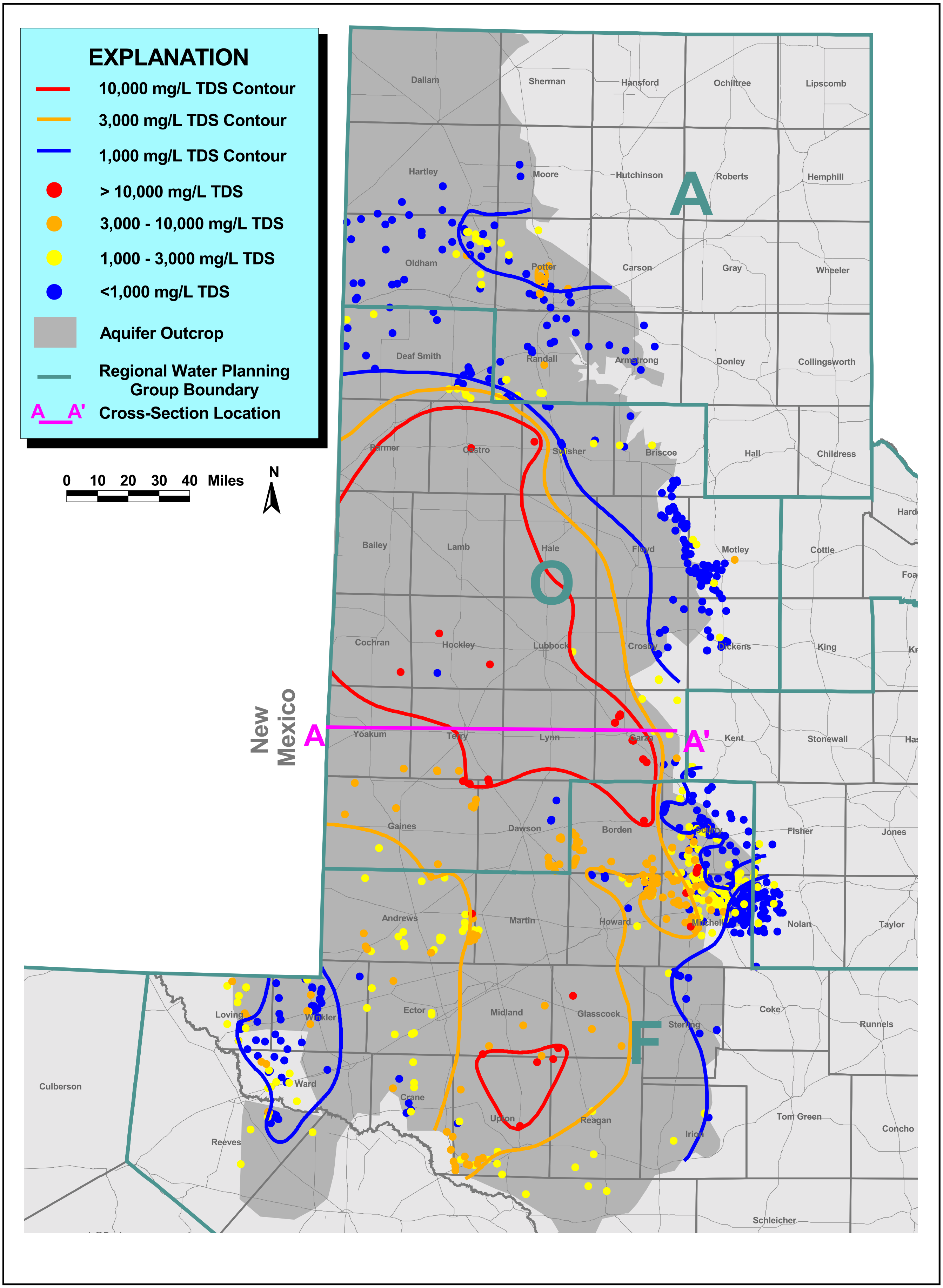
Because most of the groundwater found in the Dockum aquifer ranges from brackish to saline, it would appear to have a fairly good potential as a brackish water resource. However, much of the extent of the aquifer with poor water quality is at the center of the basin at depths of up to 2,000 feet, and much of this groundwater is saline, with TDS concentrations of greater than 10,000 mg/L. Where brackish groundwater occurs, the aquifer is thinner, reducing its production potential as a brackish resource. The most favorable areas for production that combine relatively shallow depth, higher yield, and lowest dissolved solids are more limited in extent. These more favorable areas generally exist towards the margins of the basin. Depths of wells penetrating the entire thickness of the Santa Rosa sand unit within this area are typically less than 1,000 feet. Although well yields are generally higher in these areas than in the basin center due to the coarser grained nature of the sands in this area, well yields may still be a limiting factor for using Dockum groundwater as a brackish groundwater resource. Because recharge is minimal, any withdrawal of Dockum groundwater, other than in the outcrop area, will deplete water held in storage. It is estimated that over 4 million acre-feet of groundwater is available from the Dockum in Texas, of which more than 3 million acre-feet is less than 5,000 mg/L TDS[1].

Availability- LOW to MODERATE- Much of the Dockum extent appears to contain very-saline groundwater, and is not a potential brackish resource. This includes much of the aquifer's extent in Region O. The best potential as a brackish resource occurs in the southern part of the aquifer, and even here, the availability must be considered only moderate.

Productivity- LOW- Where a brackish groundwater resource is available in the Dockum aquifer, the productivity is fairly low due to relatively low transmissivities.

Source Water Production Cost- LOW to HIGH- The nature of the Dockum is highly variable throughout its extent. Relative costs for producing groundwater may be low in the northern extent, due to the shallow and productive nature of the aquifer. In the central and southern portions of the aquifer, the thinner and less productive nature of the aquifer means more wells will have to be installed to produce a required rate of groundwater, resulting in overall higher costs.

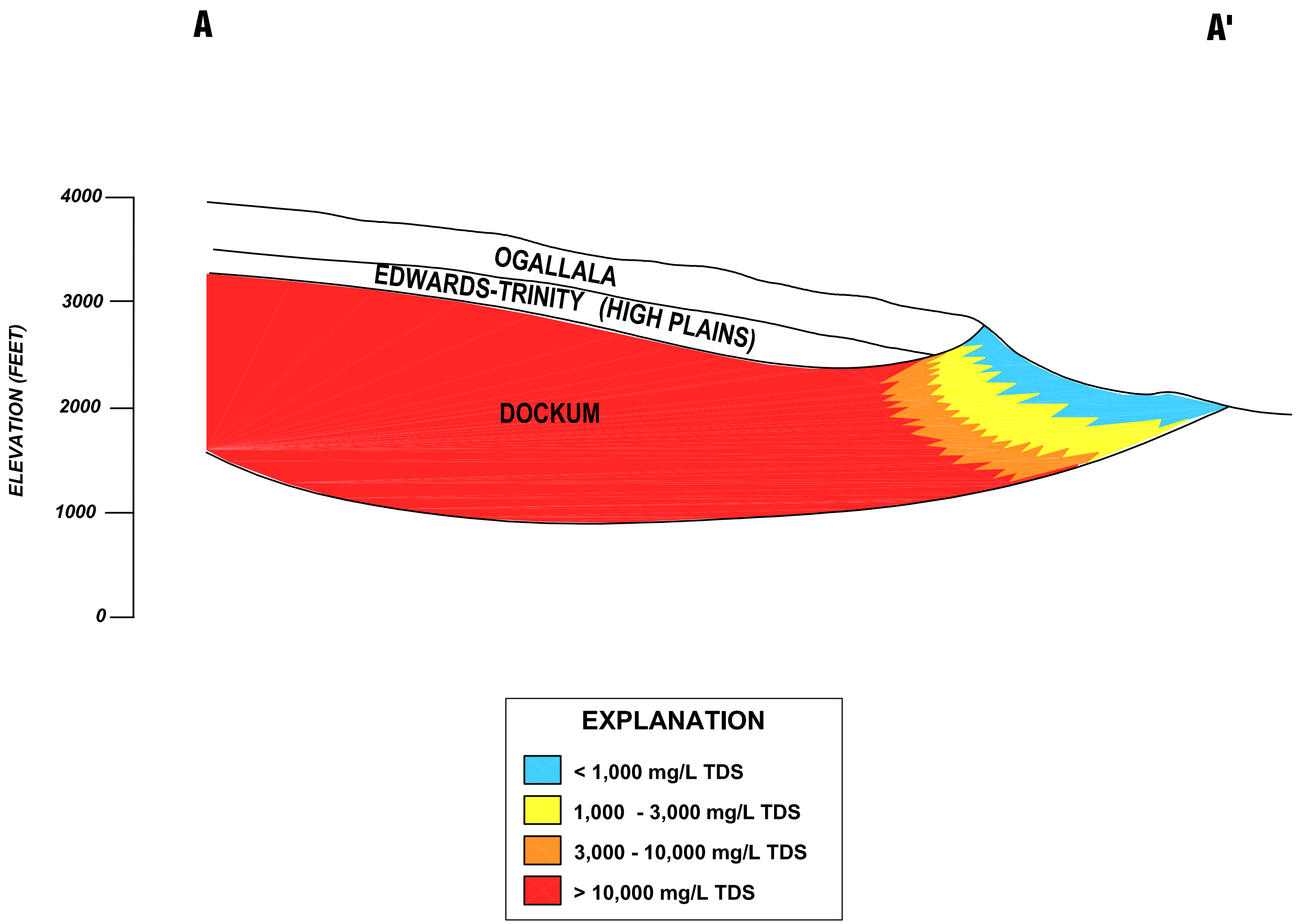
Summary of Brackish Water In the Dockum Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
A- Panhandle	Low	Low	Low
F- Region F	Moderate	Low	High
O- Llano Estacado	Low	Low	Moderate to High



GROUNDWATER QUALITY IN THE DOCKUM AQUIFER

FIGURE 39

LBG-GUYTON ASSOCIATES



SIMPLIFIED CROSS SECTION OF THE DOCKUM AQUIFER WITH GENERALIZED WATER QUALITY RANGES
(Modified from Bradley and Kalaswad, 2002)

FIGURE 40

LBG-GUYTON ASSOCIATES

3.2.8 Rita Blanca

The Rita Blanca aquifer is composed of Cretaceous and Jurassic sands and gravels and extends across Colorado, New Mexico, Oklahoma, and Texas. However only a small portion of the Rita Blanca is located within Texas in Dallam and Hartley Counties in the northwestern Texas Panhandle, as shown in Figure 41. Most of the groundwater produced from the Rita Blanca is used for irrigation. City of Texline municipal supply is derived from the aquifer.

A schematic cross section of the Rita Blanca is shown in Figure 42. The aquifer consists of the Jurassic age Exeter Sandstone and the Morrison Formation and the Cretaceous age Lytle Sandstone and Dakota Group. The Exeter is a massive sandstone up to 50 feet thick. The Morrison, a siltstone, sandstone, and mudstone, is up to 300 feet thick. The Lytle is a sandstone and conglomerate up to 90 feet thick. The Dakota Group consists of massive sandstones with some shale, and is 200 feet thick.

Most groundwater produced from the Rita Blanca is from the Lytle and Dakota units. Groundwater production from the Exeter and Morrison zones is typically limited. Groundwater in the Rita Blanca is typically found under both water table and artesian conditions. Although few aquifer test data are available for the Rita Blanca, well yields of 600 to 800 gpm are possible from Rita Blanca wells in the Cretaceous sands. However, based on similar aquifers, transmissivities are expected to average 20,000 gpd/ft, storage coefficients are expected to be about 1×10^{-4} to 1×10^{-5}, and specific yields are expected to be between 0.05 and 0.10.

Movement of groundwater is typically to the east-southeast except near local hydrologic divides and cones of depression. Water levels have declined with increased irrigation since the 1950s, especially in the southern part of Dallam County. Well depths in the aquifer range from 100 feet to over 700 feet, but average less than 300 feet.

The water quality of groundwater produced from the Rita Blanca is typically fresh but very hard. Slightly-saline water has been noted at one location in Dallam County. In addition, the Morrison Formation typically has not been extensively used as a groundwater resource because of poor water quality.

Summary

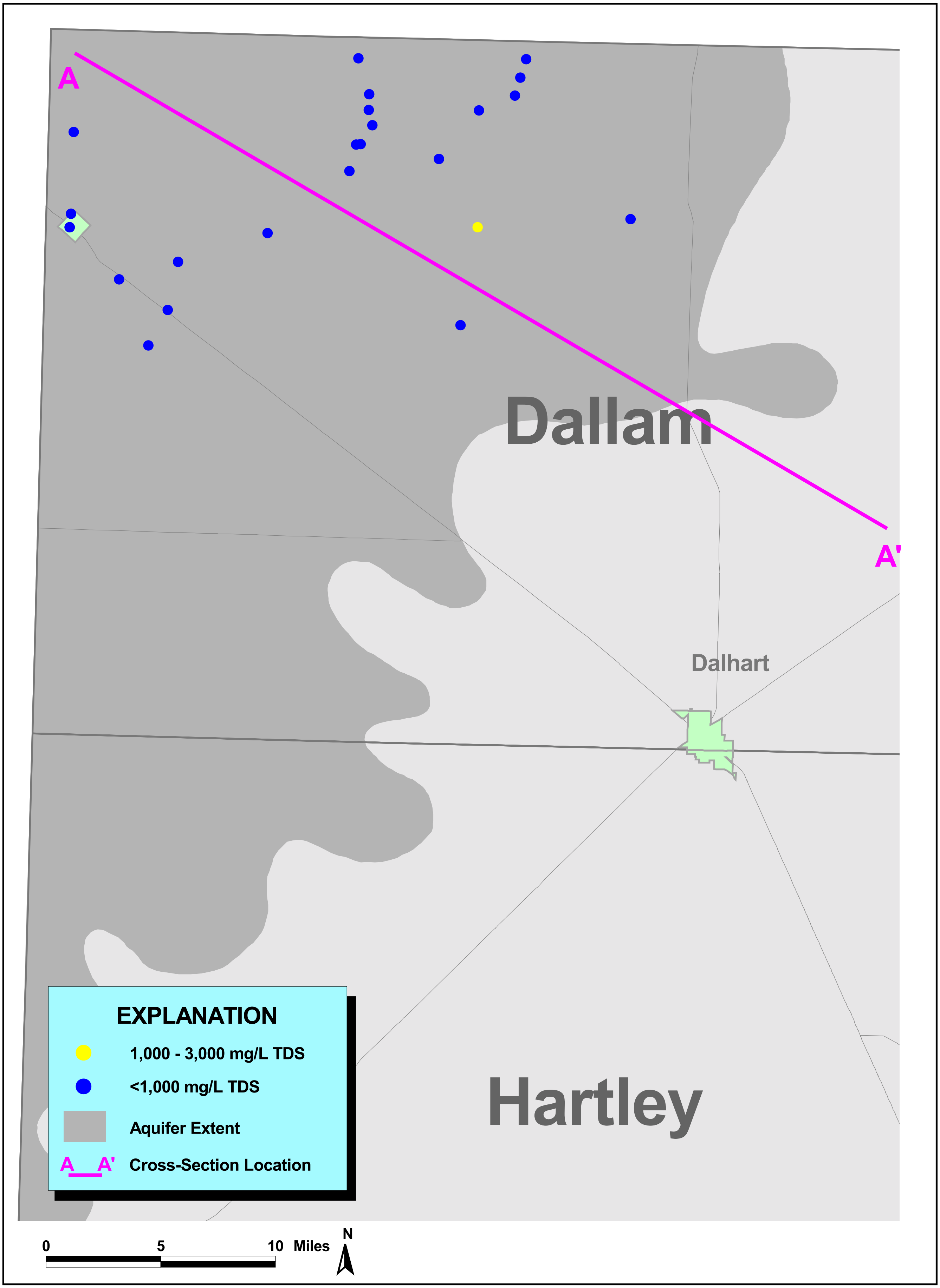
Water quality in the Rita Blanca aquifer appears to be mainly fresh with possibly a small amount of slightly-saline groundwater. Because of this, and because of the limited extent in Texas, the Rita Blanca aquifer should not be considered as a significant brackish groundwater resource.

Availability- LOW- Most groundwater produced from the Rita Blanca is fresh, and little brackish water has been found in this aquifer. Some producing zones may contain brackish water reserves, however there is currently no data to evaluate this potential.

Productivity- LOW to MODERATE - Well yields vary, but can range up to 800 gpm. However, aquifer zones producing brackish water likely have low transmissivities.

Source Water Production Cost- MODERATE- Depths of Rita Blanca wells are less than 700 feet, and average less than 300 feet. Well yields vary, but can be as high as 800 gpm. This would result in a relatively moderate production cost if brackish groundwater were found to be available.

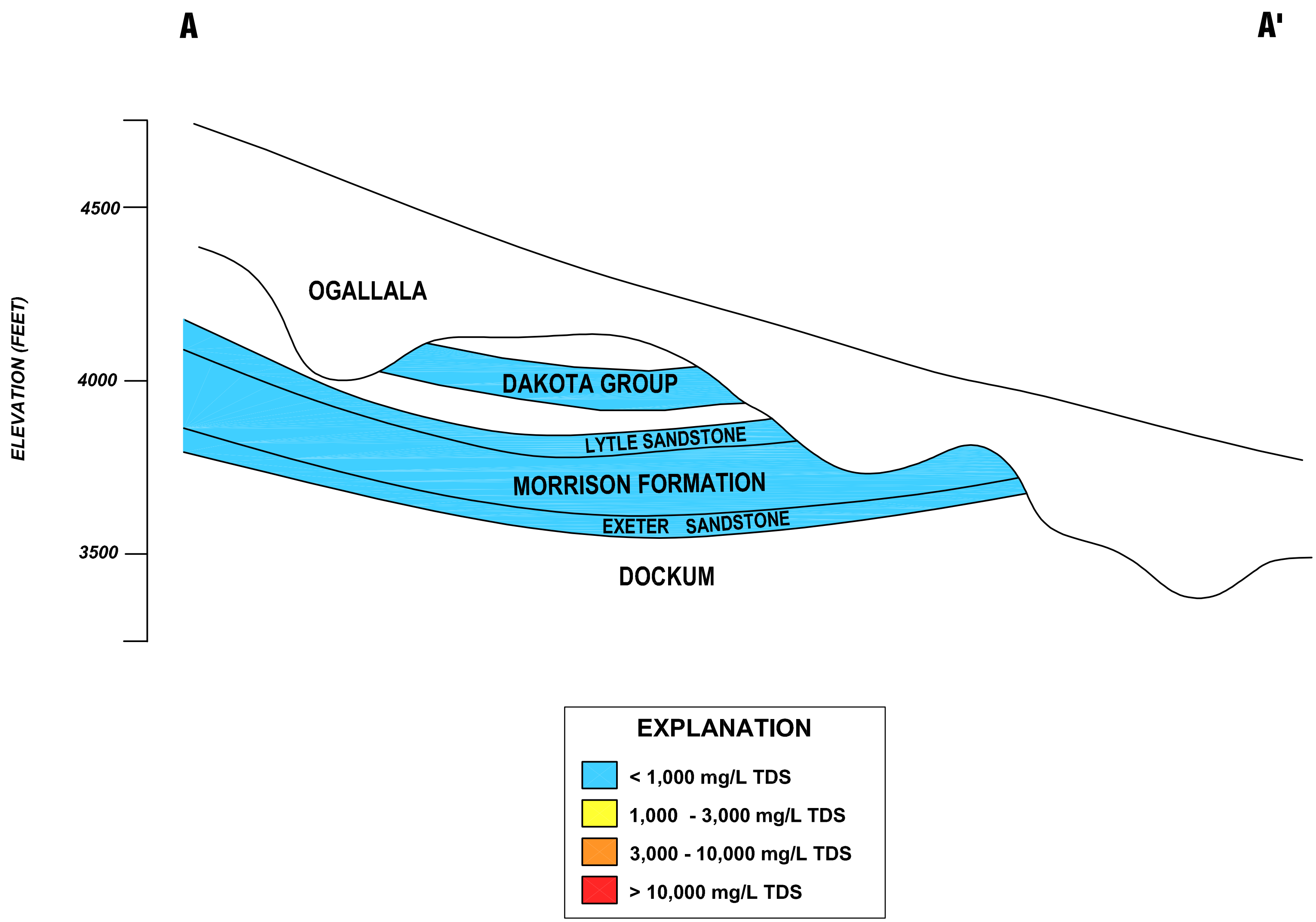
Summary of Brackish Water In the Rita Blanca Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
A- Panhandle	Low	Low to Moderate	Moderate



GROUNDWATER QUALITY
IN THE RITA BLANCA AQUIFER

FIGURE 41

LBG-GUYTON ASSOCIATES



SIMPLIFIED CROSS SECTION OF THE RITA BLANCA AQUIFER WITH GENERALIZED WATER QUALITY RANGES

(Modified from Christian, 1989)

FIGURE 42

LBG-GUYTON ASSOCIATES

3.2.9 Edwards-Trinity (High Plains)

The Edwards-Trinity (High Plains) aquifer is a Cretaceous age aquifer that underlies the Ogallala aquifer in sixteen counties of the south-central Texas High Plains and eastern New Mexico, as shown in Figure 43. Groundwater currently produced from the Edwards-Trinity (High Plains) aquifer is mainly used for irrigation purposes.

The Edwards-Trinity (High Plains) aquifer is up to 300 feet thick and is comprised of two zones, as shown in the cross section in Figure 44. The deeper zone is comprised of the water-bearing sandstone deposits of the Antlers Formation of the Trinity Group. The second zone is the limestones of the Edwards and Comanche Peak Formations of the Fredericksburg Group. The Antlers is primarily composed of quartz sand and sandstone interbedded with clay, siltstone, and gravel lenses, overlying a basal conglomerate layer. Formation thickness is irregular; maximum thickness is 60 feet, and thins towards the northwest. The average depth to the Antlers from land surface is 200 to 350 feet. The Walnut Formation separates the Antlers from the overlying Comanche Peak and Edwards Limestones. The Comanche Peak is a limestone with a maximum thickness of 85 feet, and the Edwards is a massive limestone with a maximum thickness of 35 feet. Enlarged fracture sets and solution features are common in the Edwards.

The average well yield for Antlers wells range from 50 to 200 gpm, although yields can be as high as 1,000 gpm. Aquifer test data for wells in the Antlers are limited, but the available data indicate that specific capacities in Antlers wells are generally less than 2 gpm/ft, and that the aquifer has very low storage coefficients. In the Edwards and Comanche Peak limestones, well yields can be more than 800 gpm, with yields of 250 gpm being normal in some areas. Pumping tests indicate that specific capacities of Edwards and Comanche Peak wells range widely, from as low as 2 gpm/ft to more than 60 gpm/ft. Aquifer characteristics of the Edwards-Trinity (High Plains) aquifer have not been widely reported, but transmissivities should average approximately 2,000 gpd/ft, storage coefficients are estimated to be approximately 1×10^{-4} to 1×10^{-5}, and specific yields should be between 0.02 and 0.05.

Water levels in the Edwards-Trinity (High Plains) aquifer are higher than the overlying Ogallala in some places, and in these areas water from the Edwards-Trinity (High Plains) moves upward into the Ogallala. In other areas water levels in the Edwards-Trinity (High Plains) are lower than in the Ogallala, and here water moves downward from the Ogallala into the Edwards-Trinity (High Plains). The Ogallala Formation often directly overlies the Edwards Formation, and most wells drilled in the Edwards-Trinity are also screened in the Ogallala. Some movement into the Edwards-Trinity (High Plains) from the underlying Dockum aquifer also likely occurs.

The groundwater quality in the Antlers Formation tends to be fresh to slightly-saline, and tends to be a sodium or calcium bicarbonate. In the Edwards and Comanche Peak limestones, groundwater is also generally fresh to slightly-saline and tends to be a mixed cation or sodium bicarbonate type. Groundwater from both zones becomes notably poorer near saline/playa lakes and where gypsum beds are found. In these areas, the TDS concentrations can be as high as 6,000 mg/L and the groundwater becomes a sodium-chloride or sodium-sulfate type. Areas of poorer water quality are located primarily in Lynn County and northeast Gaines County, where the TDS in Edwards-Comanche Peak is usually greater than 3,000 mg/L. The TDS in the Antlers has been measured at over 6,000 mg/L.

Summary

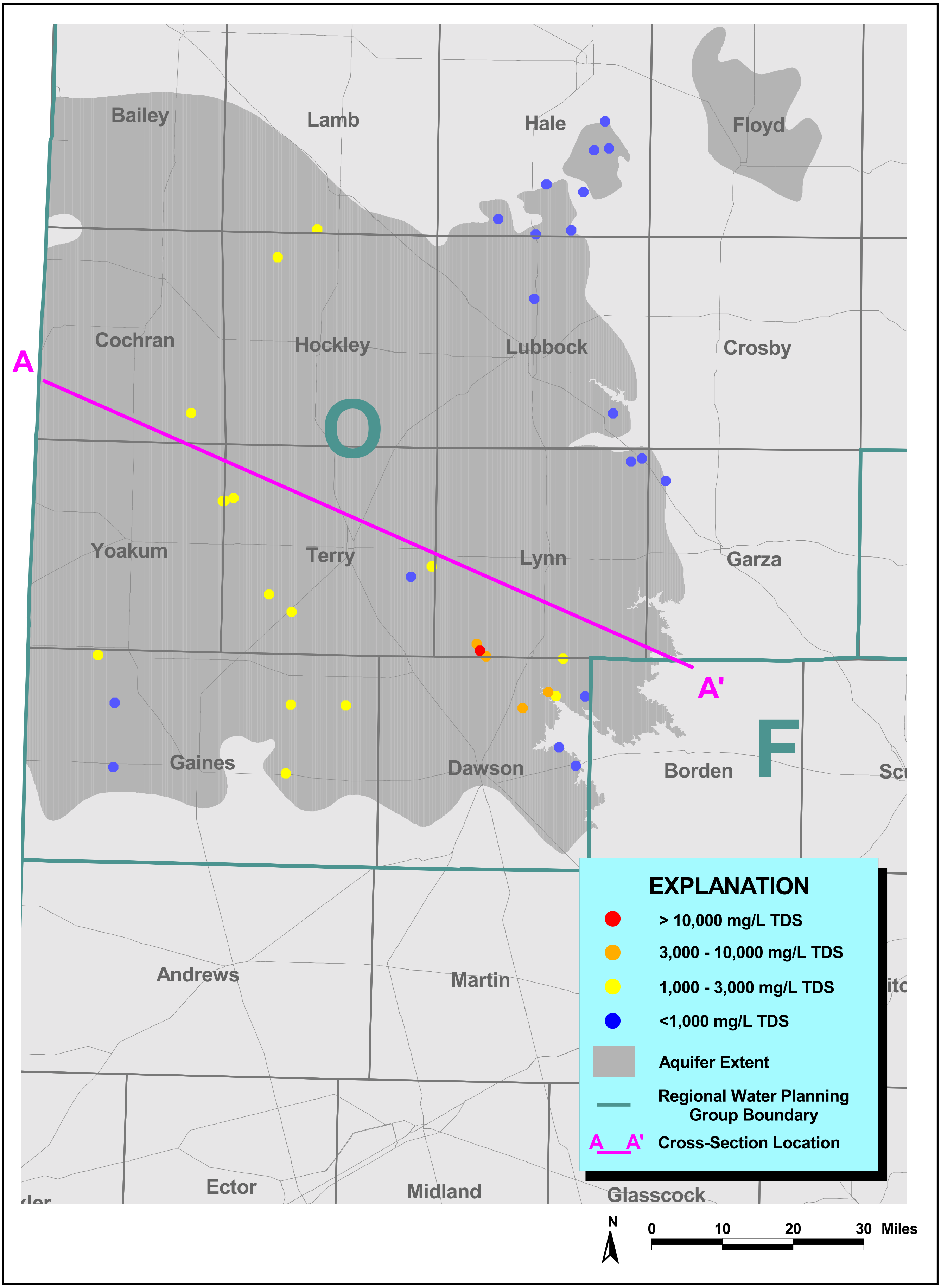
It is estimated that the Antlers contains approximately 3 million acre-feet of recoverable groundwater, and that the Edwards-Comanche Peak stores about 1.5 million acre-feet[1]. Because the majority of the Edwards-Trinity aquifer appears to contain slightly-saline water, it should be considered as a potential brackish groundwater resource.

Availability- HIGH- A significant portion of the Edwards-Trinity (High Plains) aquifer contains slightly- to moderately-saline groundwater, and, potentially millions of acre-feet have been estimated to be available from this aquifer.

Productivity- LOW- Although the aquifer is encountered at relatively shallow depths, the low transmissivities expected for the aquifer make the productivity of the Edwards-Trinity (High Plains) aquifer low.

Source Water Production Cost- MODERATE- Well yields are moderate from the Edwards-Trinity (High Plains) aquifer, and depths to groundwater are generally less than 500 feet. This results in a moderate expected source water production cost for brackish groundwater from this aquifer.

Summary of Brackish Water In the Edwards-Trinity (High Plains) Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
F- Region F	None	--	--
O- Llano Estacado	High	Low	Moderate



GROUNDWATER QUALITY IN THE EDWARDS-TRINITY (HIGH PLAINS) AQUIFER

FIGURE 43

LBG-GUYTON ASSOCIATES

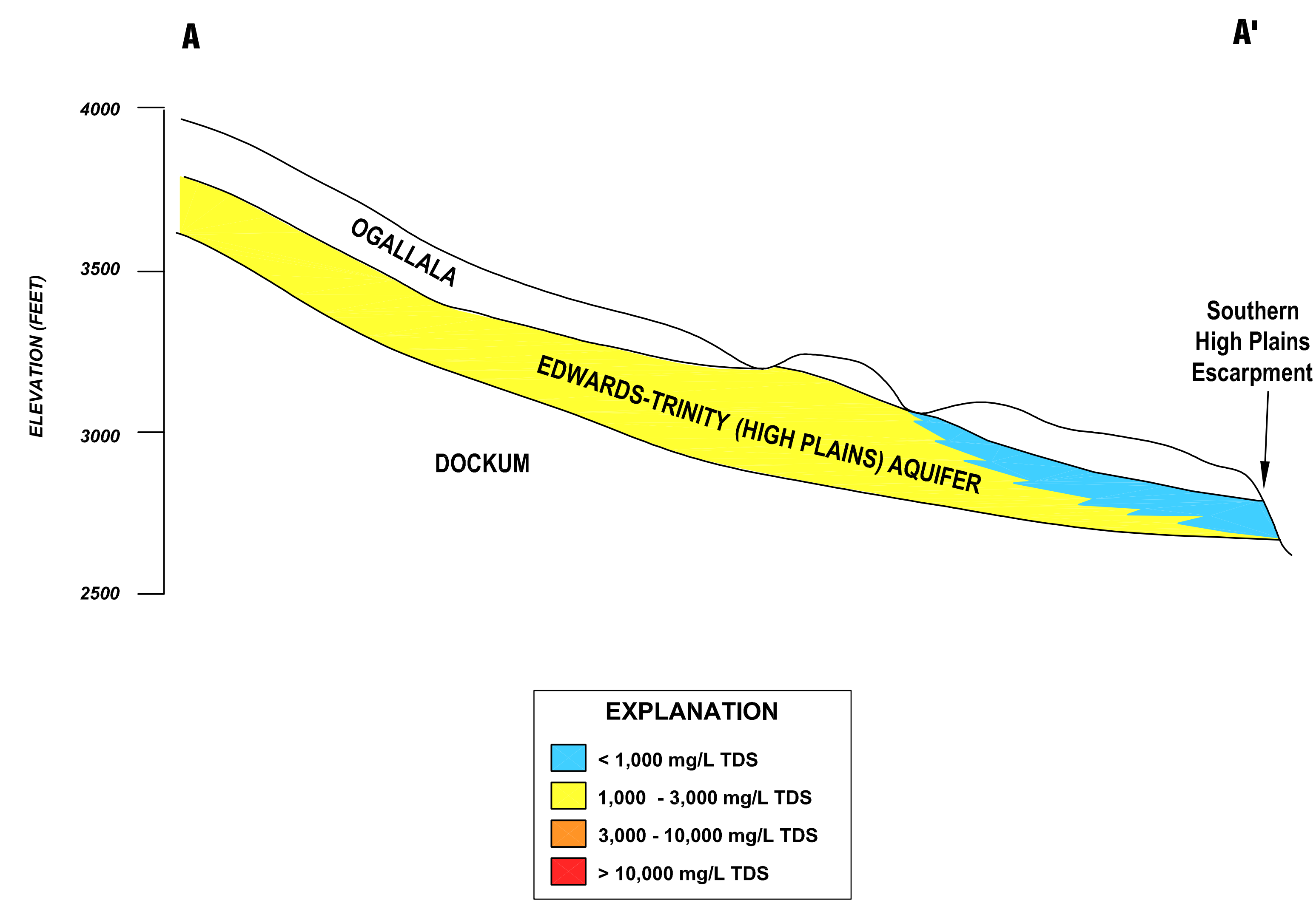


FIGURE 44

SIMPLIFIED CROSS SECTION OF THE EDWARDS-TRINITY (HIGH PLAINS) AQUIFER WITH GENERALIZED WATER QUALITY RANGES

(Modified from Fallin, 1989)

3.2.10 Blaine

The Blaine aquifer extends from Wheeler to Coke Counties in West-Central Texas, as shown in Figure 45. Most of the groundwater currently produced from the Blaine is used for irrigation purposes because the water quality is poor.

The Permian age Blaine Formation is composed of shale, sandstone, and beds of gypsum, halite, and anhydrite, some of which can be 10 to 30 feet in thick. Overall, the Blaine Formation can be up to 1,200 feet thick in the region, as shown in the cross section in Figure 46. Groundwater in the Blaine occurs in dissolution channels that have formed in the aquifer matrix. Yields from wells completed in the Blaine aquifer can be as high as 1,000 gpm. However, the productivity of a well depends on the number and size of dissolution channels intersected by the well. Because of this, it is very difficult to accurately describe hydraulic characteristics or anticipate potential well yields in the Blaine. Transmissivities will vary significantly, but are estimated to average approximately 2,000 gpd/ft, storage coefficients are estimated to average approximately 1×10^{-4}, and specific yields are estimated to average 0.02. In places, low productivity wells or even dry holes occur next to highly productive wells. Specific capacities range widely, with averages ranging from less than 5 gpm/ft to nearly 50 gpm/ft.

Recharge to the Blaine aquifer is through the infiltration of precipitation on the outcrop. This recharge then moves down-dip predominantly along dissolution channels in the gypsum, anhydrite, and halite beds. The recharge water discharges in topographically low areas to salt seeps and springs. As the water moves down-dip, it further dissolves the gypsum/anhydrite/ halite beds, increasing the number and size of solution channels that water can move through and also increasing the salinity of the groundwater. The water that discharges into salt seeps and springs tends to be very high in TDS, and will contaminate surface water bodies, which is a long recognized problem in the area.

The water quality from the Blaine aquifer varies greatly, but is generally slightly- to moderately-saline, very hard, and is dominated by calcium, magnesium, and sulfate ions. Most of the groundwater produced from the Blaine is highly mineralized because the water is largely being produced from dissolution channels within gypsum, halite, and anhydrite beds. For this reason it is largely unsuitable for any purposes except for salt tolerant irrigation. Total dissolved solids range from less than 1,000 to greater than 10,000 mg/L. Fresh groundwater from the Blaine is uncommon, and is usually found in topographically higher areas where the formation crops out, and where recharge from precipitation or possibly from overlying alluvium occurs. Groundwater from the Blaine throughout much of the outcrop area typically has between 2,000 and 4,000 mg/L TDS. Some wells show high levels of sodium and chloride in the groundwater, which may be either the result of the dissolution of halite beds in the subsurface, or the surface contamination of the aquifer by oil field brines.

Summary

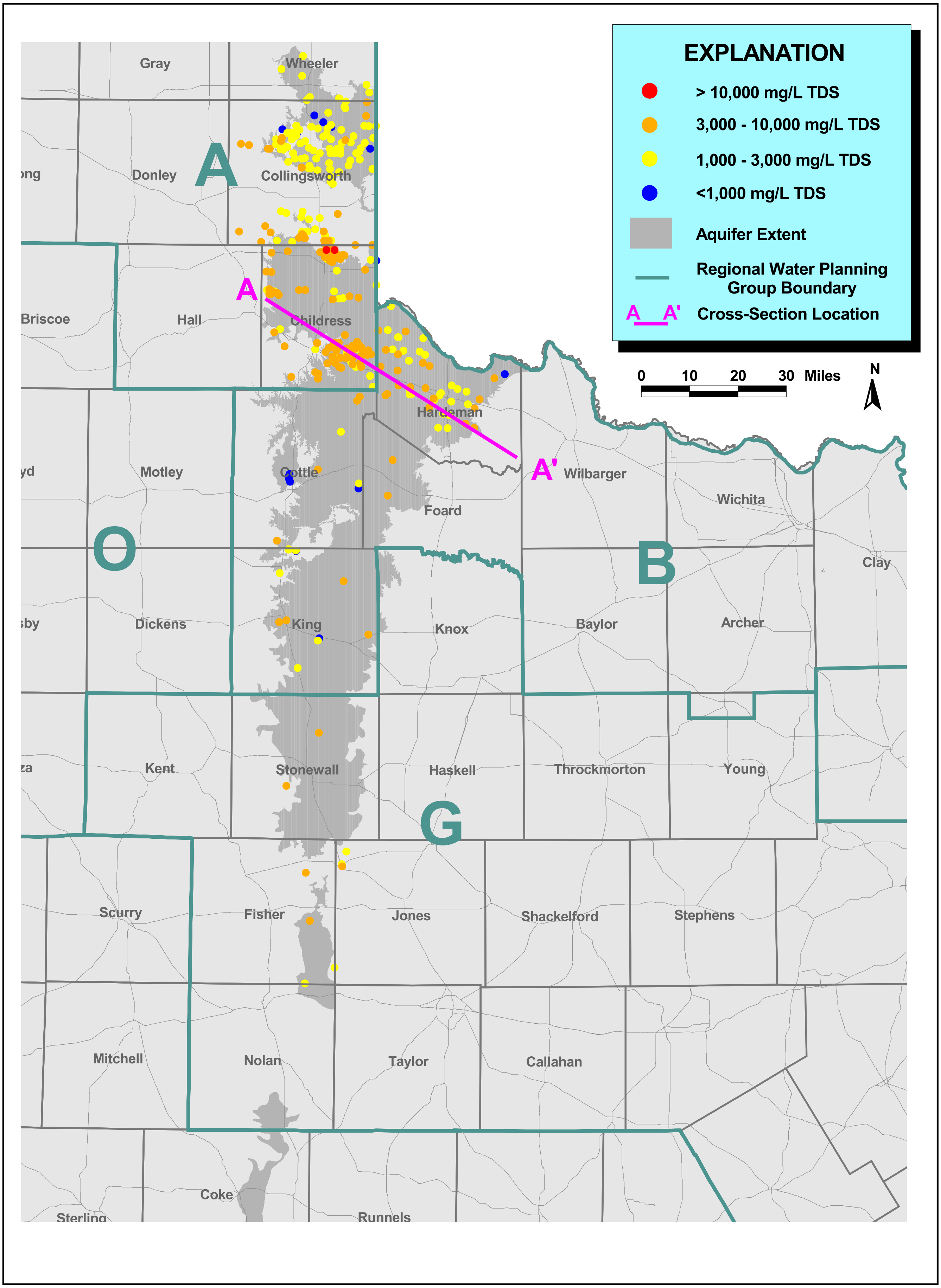
A significant amount of brackish groundwater is available from the Blaine aquifer. Previous investigators indicate that the availability of water from the Blaine is 142,600 acre-feet of both fresh and slightly-saline water and that the current use of all aquifers in their study area (Rolling Prairies region) is roughly one-half to one-third of the potential recharge to the area. Current water-quality data indicate that most of the groundwater currently produced from the Blaine aquifer is slightly- to moderately-saline. In addition, large portions of the aquifer in the southern section of the aquifer shown in Figure 45 are largely unused, increasing the amount of brackish groundwater that may be available from this aquifer.

Availability- LOW to HIGH- In the northern portion of the Blaine aquifer (Regions A and B), the availability of brackish groundwater is considered to be excellent. Here the aquifer contains a significant amount of groundwater and most of it is slightly- to moderately-saline. In Region F, the Blaine only outcrops in a very small area, and little is known about the aquifer here. In Region G, the outcrop of the Blaine is more extensive, but much less so than in the north, and the availability is expected to be much less.

Productivity- LOW to MODERATE- Well yields depend on the number and size of dissolution channels intersected by the well, and yields can vary significantly over very short distances. The overall transmissivity is expected to be relatively low, and the overall productivity of the Blaine aquifer is considered to be low to moderate.

Source Water Production Cost- MODERATE to HIGH- It is impossible to determine where productive wells will be before drilling wells or test holes, and therefore the installation of numerous wells to supply a desalination facility may cost substantially more than in a more homogeneous aquifer. If highly productive wells are able to be installed, then the costs will be substantially less. However, this cannot be planned in the feasibility portion of a project.

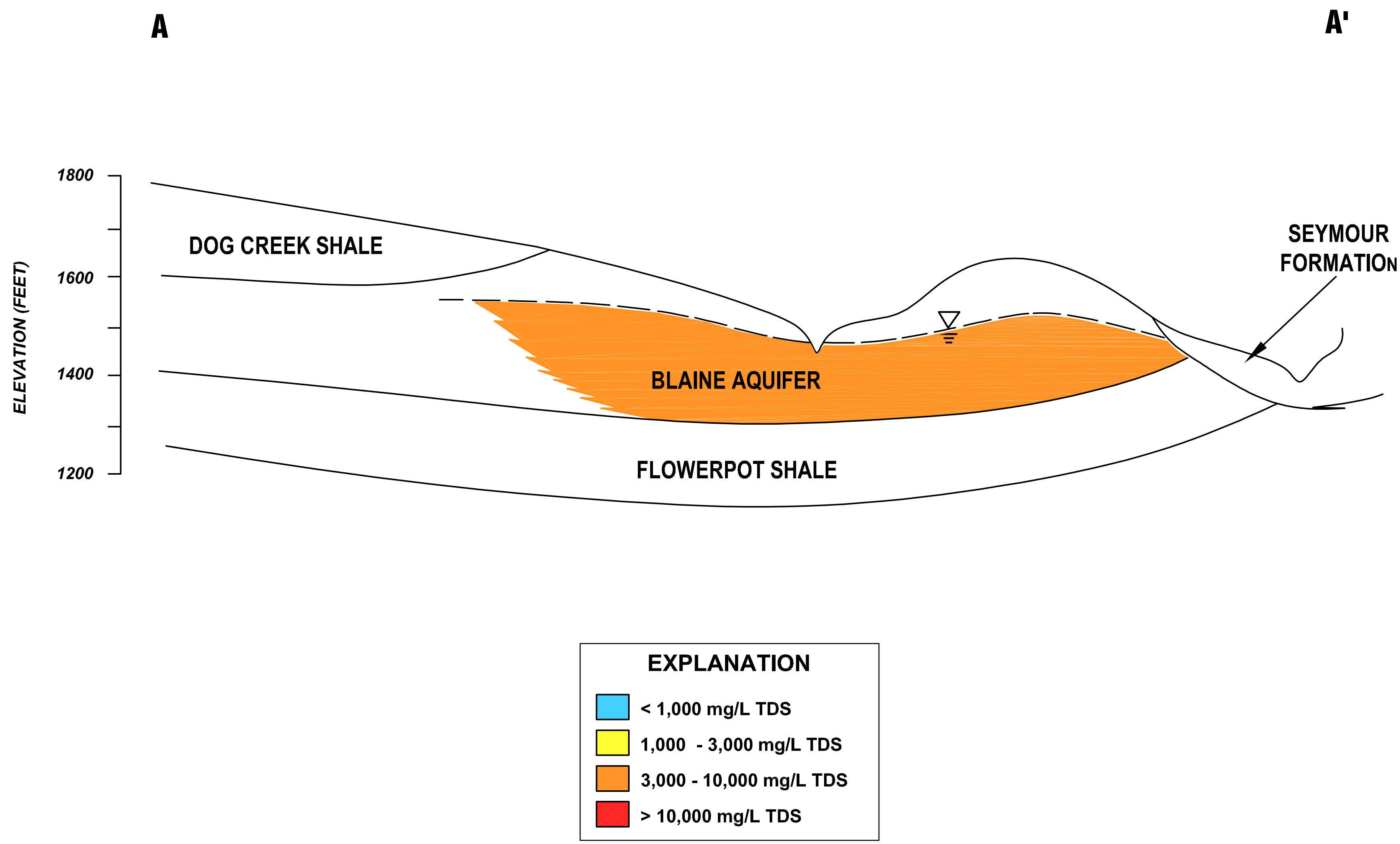
Summary of Brackish Water In the Blaine Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
A- Panhandle	High	Low to Moderate	Moderate
B- Region B	High	Low to Moderate	High
F- Region F	Unknown	Unknown	Unknown
G- Brazos	Low	Low to Moderate	Moderate



GROUNDWATER QUALITY IN THE BLAINE AQUIFER

FIGURE 45

LBG-GUYTON ASSOCIATES



SIMPLIFIED CROSS SECTION OF THE BLAINE AQUIFER WITH GENERALIZED WATER QUALITY RANGES

(Modified from Maderak, 1972)

FIGURE 46

LBG-GUYTON ASSOCIATES

3.2.11 Whitehorse-Artesia

The Whitehorse-Artesia aquifer is a Permian age aquifer located in West-Central Texas, as shown in Figure 47. The Whitehorse and Artesia aquifers have been referred to separately in several reports on the groundwater resources in the Rolling Plains region of Texas; however, they are equivalent geologic formations. Therefore, in this report this aquifer will be referred to as the Whitehorse-Artesia Group or aquifer. This aquifer is not used sufficiently enough to be designated a "minor aquifer" by the TWDB. However, it holds sufficient brackish groundwater potential to be included in this report as a separate aquifer. The Whitehorse-Artesia aquifer has been used for domestic, stock, and irrigation purposes.

The Whitehorse-Artesia Group lies above the Blaine aquifer as shown in the cross section in Figure 48. This formation consists of fine-grained red sand, light gray to red dolomite beds, and several thick, white to brown gypsum beds, and is up to 700 feet thick. The Whitehorse-Artesia crops out west of the Blaine, and yields small to moderate quantities of fresh to very- saline water to wells. In the northern portion of the aquifer, yields greater than 600 gpm are possible. In the central portion of the aquifer area, yields can be up to 1,000 gpm with specific capacities of 10 to 20 gpm/ft. However, in other areas, the highest reported yields from the Whitehorse-Artesia are less than 200 gpm. No data on aquifer characteristics are available. Transmissivities will vary significantly, but are estimated to average approximately 2,000 gpd/ft, storage coefficients are estimated to average approximately 1×10^{-4}, and specific yields are estimated to average 0.02.

Water quality from the Whitehorse-Artesia aquifer varies greatly. It is generally similar to groundwater from the Blaine aquifer, with moderately high concentrations of calcium, sulfate, but generally has a lower TDS than the Blaine. In the northern portion of the aquifer, many wells are producing fresh groundwater, as shown in Figure 47. As with the Blaine, water quality from the Whitehorse-Artesia is fresh primarily in recharge areas, and TDS increases in down-dip portions of the aquifer.

Summary

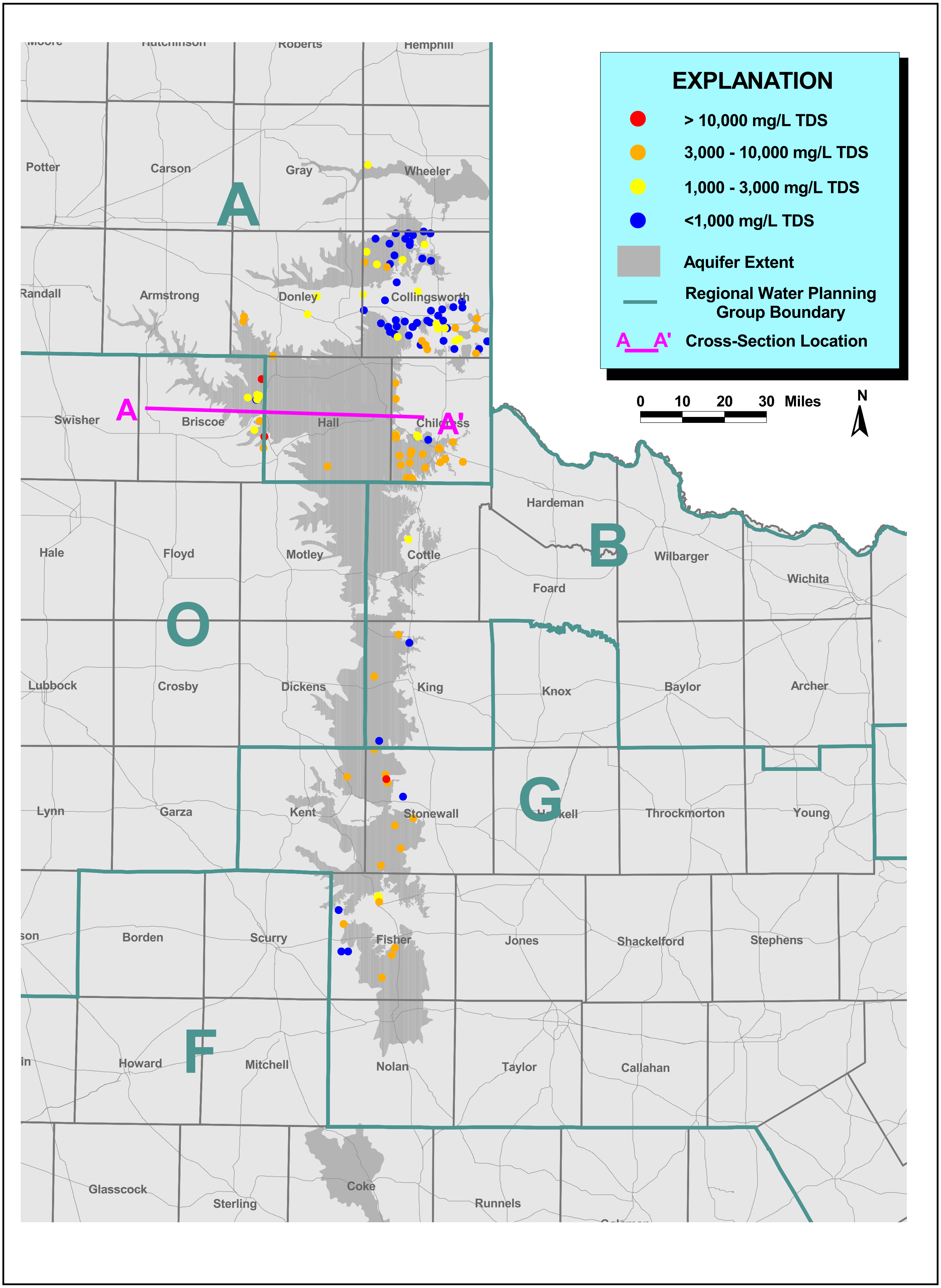
No estimates of availability of water from the Whitehorse-Artesia have been made, and conclusions cannot be based upon the very few data that exist. However, because of the nature of the Whitehorse-Artesia aquifer, which is similar to the adjacent Blaine aquifer, it should be considered as a good brackish groundwater resource.

Availability- MODERATE to HIGH- The availability of brackish groundwater from the Whitehorse-Artesia is considered to be moderate to high. It does not hold the potential of the Blaine aquifer, but still has the potential to be a reasonable source of brackish groundwater.

Productivity- LOW to MODERATE- The variable nature and low transmissivities expected from the Whitehorse-Artesia aquifer result in low to moderate productivity.

Source Water Production Cost- MODERATE- Low to moderate production from shallow wells result in a moderate relative cost for producing groundwater from the Whitehorse-Artesia aquifer.

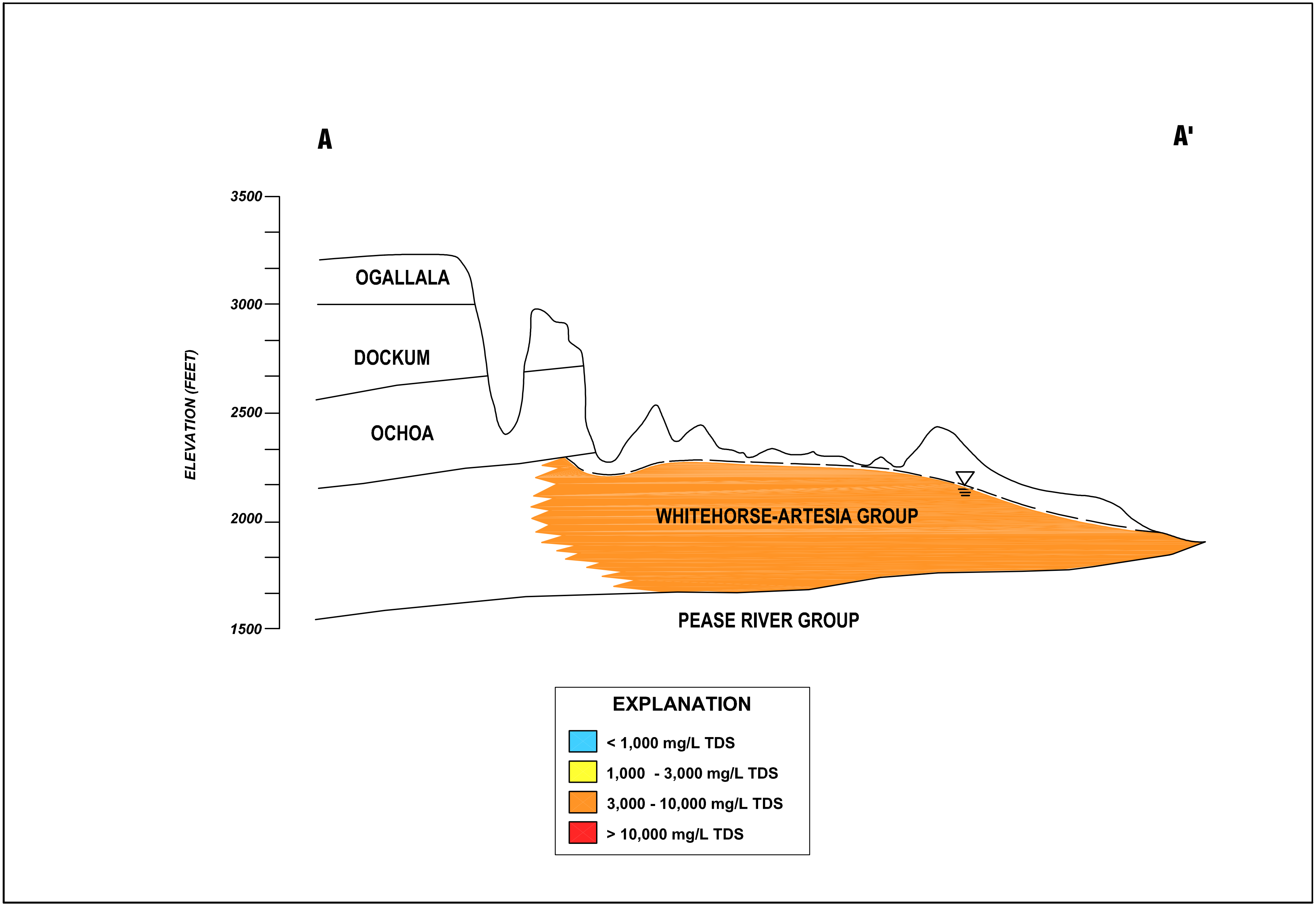
Summary of Brackish Water In the Whitehorse-Artesia Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
A- Panhandle	High	Low to Moderate	Moderate
B- Region B	Unknown	Low to Moderate	Moderate
F- Region F	Moderate	Low to Moderate	Moderate
G- Brazos	Unknown	Low to Moderate	Moderate
O- Llano Estacado	Moderate	Low to Moderate	Moderate



GROUNDWATER QUALITY IN THE WHITEHORSE-ARTESIA AQUIFER

FIGURE 47

LBG-GUYTON ASSOCIATES



SIMPLIFIED CROSS SECTION OF THE WHITEHORSE-ARTESIA AQUIFER WITH GENERALIZED WATER QUALITY RANGES

(Modified from Popkin, 1973b)

FIGURE 48

LBG-GUYTON ASSOCIATES

3.2.12 Lipan

The Lipan aquifer occurs in Concho, Runnels and Tom Green Counties, as shown in Figure 49. Groundwater produced from the Lipan is principally used for irrigation and livestock, with limited amounts used for rural domestic and municipal purposes. Most of the current production from the Lipan aquifer occurs in Tom Green County.

A schematic cross section of the Lipan is shown in Figure 50. The Lipan aquifer is comprised of saturated alluvial deposits of the Quaternary-age Leona Formation and the up-dip, hydrologically connected portions of the underlying Choza and Bullwagon Formations. The total thickness of the alluvium that comprises the Lipan ranges from a few feet to about 125 feet. Groundwater in the Lipan aquifer exists under water-table conditions, and the saturated thickness of the Leona alluvial sediments ranges from zero to over 100 feet. Transmissivities are estimated to average approximately 20,000 gpd/ft, with specific yields estimated to be between 0.05 and 0.10. Well yields from the aquifer range from 100 to 1,000 gpm. Recharge is through the infiltration of precipitation on the aquifer outcrop. Discharge from the aquifer is primarily to wells but also to seepage to the Concho River, other streams in the area, and to evapotranspiration. Water levels in the aquifer vary significantly during the irrigation season when the aquifer is heavily pumped. However, long-term, winter, static water-levels in the aquifer have remained relatively stable. Few aquifer test data exist with which to estimate aquifer characteristics.

The water quality in the Lipan aquifer ranges from fresh to moderately-saline and is very hard. The chemical quality often does not meet drinking water standards, but is generally suitable for irrigation. Some shallow groundwater in the aquifer has been impacted by man-made sources, including the introduction of fertilizers that have resulted in high nitrates, oil-field operations, seasonal heavy irrigation pumpage that has encouraged the upward migration of poorer quality water from deeper zones, and irrigation return flow that has concentrated minerals in the water through evaporation and the leaching of natural salts from the unsaturated zone. These have all had localized impacts on the Lipan water quality.

Summary

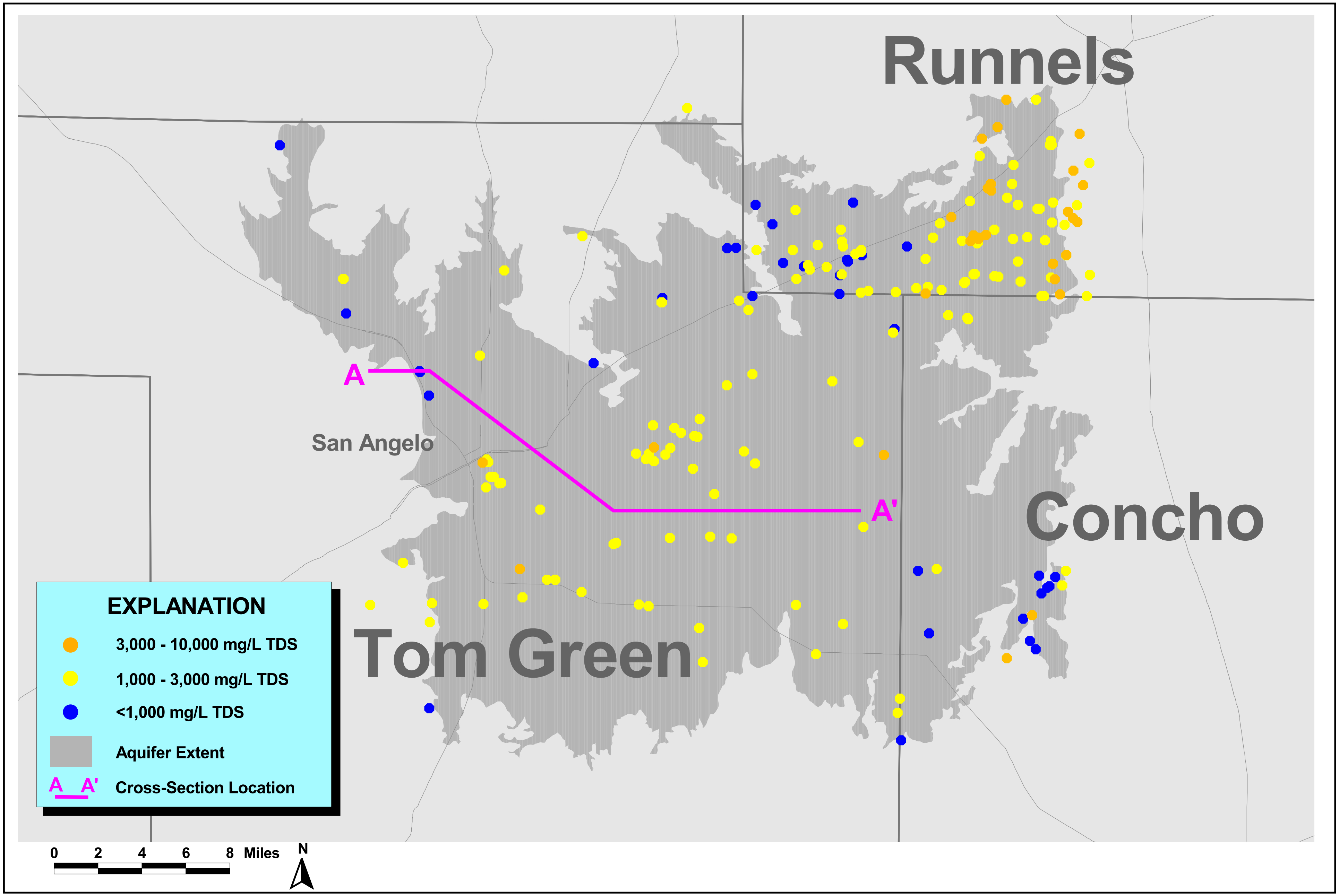
The Lipan should be considered a good potential source of brackish groundwater over most of the aquifer. Because of the relatively transmissive nature of alluvial aquifers, and the shallow depth that the groundwater is found, the brackish groundwater should be practical to recover at relatively low costs.

Availability- HIGH- Because most of the groundwater in the Lipan aquifer is slightly- to moderately-saline, it should be considered a good potential source of brackish water.

Productivity- MODERATE- Brackish groundwater can be easily located in the Lipan aquifer. Because of the very shallow nature of the Lipan, and the potential for moderate to large capacity wells, the productivity of this aquifer is considered to be moderate.

Source Water Production Cost- LOW to MODERATE- The Lipan is very shallow in nature, and has the potential to produce moderate to large quantities of water to wells. This results in a low to moderate relative cost for the production of brackish groundwater.

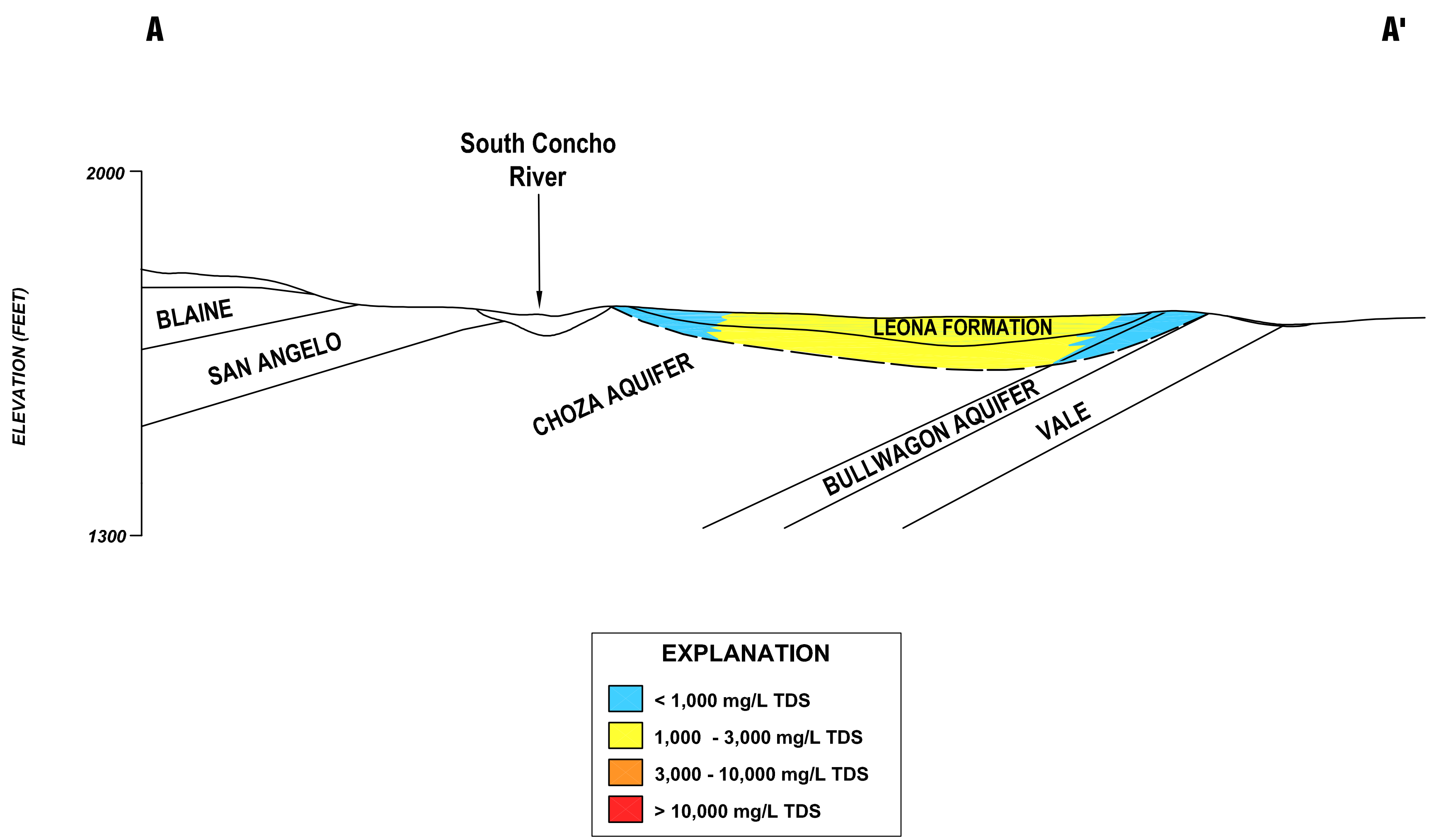
Summary of Brackish Water In the Lipan Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
F- Region F	High	Moderate	Low to Moderate



GROUNDWATER QUALITY
IN THE LIPAN AQUIFER

FIGURE 49

LBG-GUYTON ASSOCIATES



SIMPLIFIED CROSS SECTION OF THE LIPAN AQUIFER WITH GENERALIZED WATER QUALITY RANGES

(Modified from Lee, 1986)

FIGURE 50

LBG-GUYTON ASSOCIATES

3.2.13 Hickory

The Hickory aquifer occurs in 19 counties in the Llano Uplift region of Central Texas, as shown in Figure 51. Most of the water currently pumped from the Hickory is used for irrigation and livestock purposes, with a smaller amount used for municipal supply purposes. Most of the pumpage from the Hickory occurs in Mason County, where almost all is used for irrigation.

A schematic cross section of the Hickory is shown in Figure 52. The Cambrian age Hickory Sandstone is located around the exposed Precambrian rocks that form the Llano Uplift. Outcrops of the Hickory are discontinuous, and block faulting has compartmentalized much of the aquifer, restricting groundwater flow in some areas. The down-dip, confined portion of the aquifer encircles the uplift and extends to depths greater than 4,500 feet.

Hickory groundwater is generally found under water-table conditions in the outcrop area and under artesian conditions down-dip. A majority of the groundwater production occurs in the outcrop area. Transmissivity estimates range from 5,000 to over 40,000 gpd/ft and confined storage coefficients range from 1 x 10^{-1} to 1 x 10^{-4}, and specific yields near the outcrop are estimated to be 0.10 to 0.15. Yields of large-capacity wells usually range between 200 and 500 gpm, although some wells have yields in excess of 1,000 gpm. The highest well yields are typically found northwest of the Llano Uplift, where the aquifer has the greatest saturated thickness. Typical well depths near the outcrop range from 50 to 200 feet, and can be as deep as 2,000 to 5,000 feet deep at the outer down-dip extents of the aquifer.

Recharge to the Hickory aquifer is from the infiltration of precipitation on the outcrop and from the downward leakage from the overlying Trinity aquifer. The amount of recharge from precipitation is limited due to the discontinuous and limited extent of the outcrop of the Hickory in the area. The amount of recharge from the Trinity is unknown. Groundwater flow is from the recharge areas to down-dip areas. Generally, groundwater flows radially down-dip away from the central part of the Llano Uplift. Discharge from the Hickory is to wells and through cross-formational leakage to overlying units.

Figure 51 shows the groundwater quality in the Hickory aquifer. Groundwater from the aquifer is generally fresh near the outcrop of the aquifer and up to 30 miles down-dip. However, the aquifer also contains sporadic occurrences of water with 1,000 to 3,000 mg/L TDS throughout the entire extent of the aquifer as well as in the down-dip portions of the aquifer. There are very few wells with water-quality data or geophysical logs that exist in areas of the Hickory containing moderately-saline groundwater, and therefore the estimate of the 10,000 mg/L TDS line is largely speculative. The down-dip extent of water containing greater than 3,000 mg/L TDS is limited on the south, east, and southeastern side of the uplift due to structural controls that limit the extent of the aquifer in those areas. On the northwest extent of the aquifer, the water quality degrades quickly from 1,000 mg/L TDS to greater than 10,000 mg/L TDS in the down-dip portions of the aquifer.

Summary

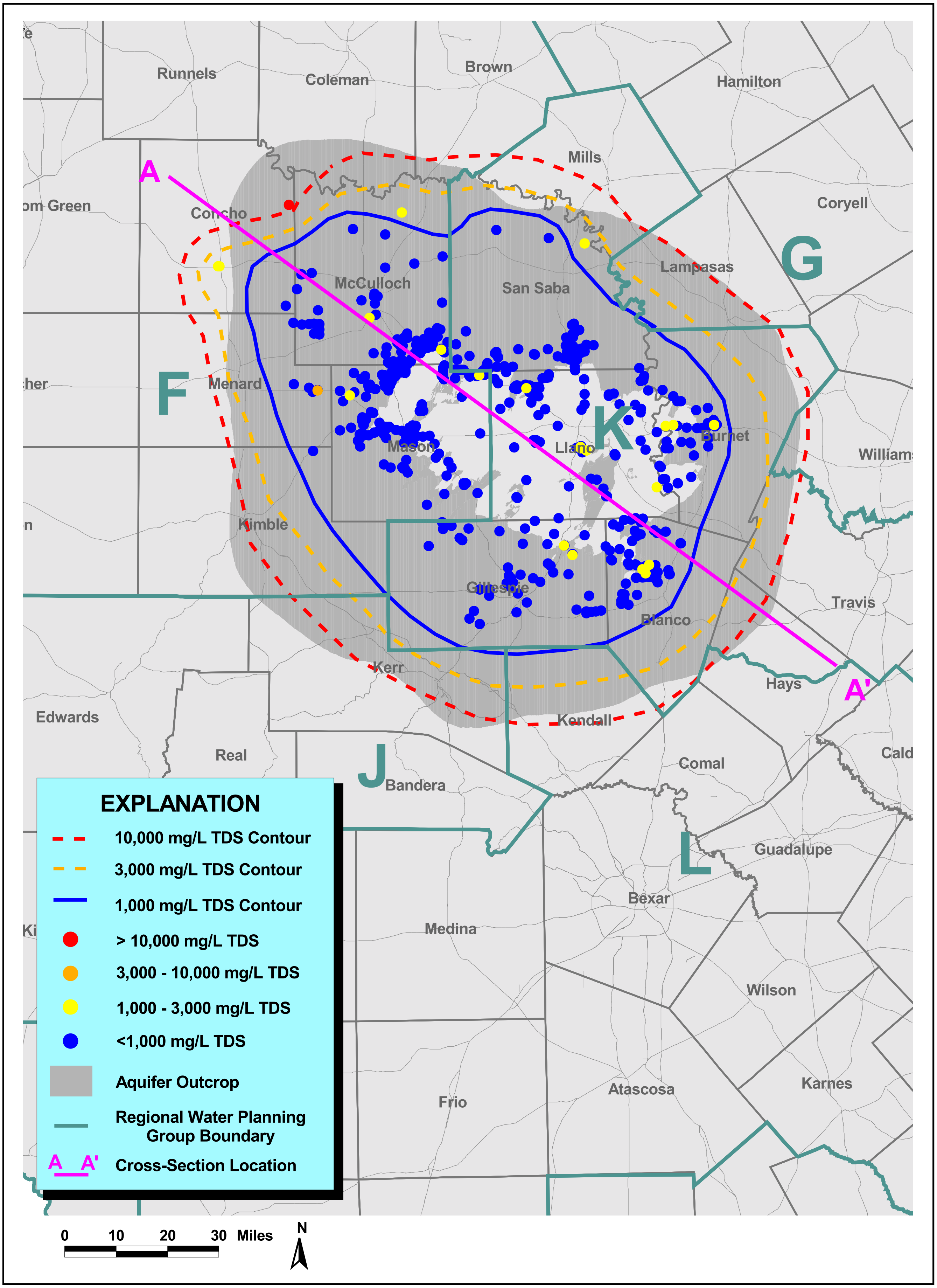
In general, little is known about the Hickory aquifer, especially about the down-dip sections of the aquifer where the brackish water resources are located. Based on available data, the Hickory is considered to have average potential as a brackish groundwater supply in down-dip areas. However, due to higher levels of radium found in some areas of the aquifer, it would be optimal to locate areas in the aquifer that have lower radium concentrations or to develop treatment and waste disposal alternatives that effectively deal with the radium issue.

Availability- LOW to MODERATE- In much of the aquifer's extent, so little is known about the Hickory that estimates of availability are speculative. In regions with relatively large portions of the Hickory, the availability of brackish groundwater is expected to be low to moderate.

Productivity- MODERATE- The lower transmissivity in the down-dip portions of the Hickory make the productivity of using this aquifer as a brackish resource only moderate.

Source Water Production Cost- MODERATE to HIGH- Due to the deeper nature and lower productivity of the brackish portion of the aquifer, the relative production costs are expected to be moderate to high.

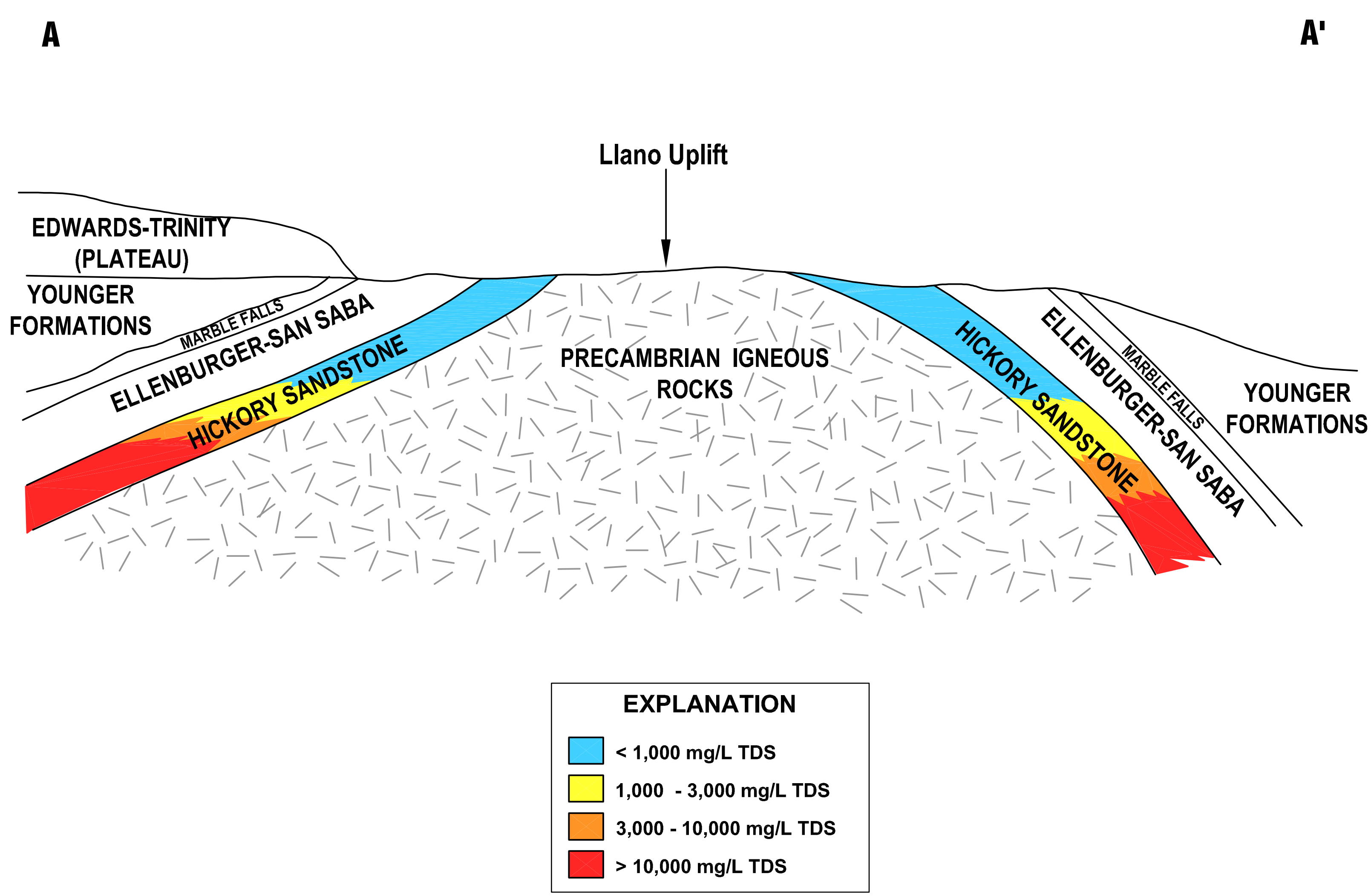
Summary of Brackish Water In the Hickory Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
F-Region F	Moderate	Moderate	Moderate to High
G-Brazos	Unknown	Moderate	Moderate to High
J-Plateau	Unknown	Moderate	Moderate to High
K-Lower Colorado	Low	Moderate	Moderate to High
L-South Central Texas	Unknown	Moderate	Moderate to High



GROUNDWATER QUALITY
IN THE HICKORY AQUIFER

FIGURE 51

LBG-GUYTON ASSOCIATES



SIMPLIFIED CROSS SECTION OF THE HICKORY AQUIFER WITH GENERALIZED WATER QUALITY RANGES
(Modified from Barker and others, 1994)

FIGURE 52

LBG-GUYTON ASSOCIATES

3.2.14 Ellenburger-San Saba

The Ellenburger-San Saba aquifer is a Cambrian age limestone and dolomite aquifer that occurs in parts of 15 counties in the Llano Uplift area of Central Texas, as shown in Figure 53. Most of the water produced from this aquifer is used for municipal water supply, mainly in Mason, McCulloch, and Menard Counties. The cities of Fredericksburg, Johnson City, Bertram, and Richland Springs have all used the Ellenburger-San Saba aquifer as a public water supply. It is important to note that the extent of the aquifer shown in Figure 53 is only that portion in the Llano Uplift area, where the fresh water aquifer occurs. The Ellenburger is also a very extensive formation throughout West Texas, and may contain substantial brackish groundwater beyond the area shown in Figure 53.

The Ellenburger-San Saba aquifer consists of limestones and dolomites of the San Saba Member of the Wilberns Formation and the Ellenburger Group. The Ellenburger-San Saba was highly eroded prior to being covered by sediments, which results in a large variation in thickness, ranging from 0 to 1,000 feet. The aquifer generally encircles the Llano Uplift, and the down-dip portion extends to depths of approximately 3,000 feet below land surface, as shown in Figure 54. In some areas the overlying beds are thin or absent, and here the Ellenburger-San Saba aquifer may be hydrologically connected to the Marble Falls aquifer. Local and regional block faulting has significantly compartmentalized the Ellenburger-San Saba, but dissolution along such faulting and related fractures has formed various sized cavities that are the major water-bearing features of the aquifer.

Groundwater in the aquifer is found mostly under artesian conditions, even in much of the outcrop area. The depth to groundwater varies from 30 to over 200 feet below ground surface. Transmissivity estimates range from 50,000 to 125,000 gpd/ft, storage coefficients are estimated to be 1×10^{-3} to 1×10^{-4}, and specific yields are estimated to be 0.03 to 0.05. Production from public supply and irrigation well yields range from 200 to 1,500 gpm, although most other wells generally yield less than 100 gpm. The average well yield from all types of wells is about 65 gpm.

As shown in Figure 53, groundwater near the outcrop of the Ellenburger-San Saba aquifer, and in some cases up to 20 miles down-dip, is generally fresh. TDS concentrations in the Ellenburger-San Saba aquifer generally increase with distance down-dip. Fresh groundwater is found mainly in areas where active recharge and flow occurs in the aquifer near the outcrop. While fresh groundwater is mostly found in areas near the outcrop, the aquifer also contains irregular occurrences of slightly-saline groundwater near the outcrop area. The down-dip extent of water containing more than 3,000 mg/L TDS ranges from about 10 miles on the south side of the outcrop to over 60 miles to the northwest of the outcrop. The down-dip extent of water containing greater than 3,000 mg/L TDS is limited on the south, east, and southwestern side of the uplift due to structural controls that limit the extent of the aquifer in those regions.

Summary

The Ellenburger-San Saba aquifer may be a potential source for small to moderate volumes of brackish groundwater in the Llano Uplift area. However, the development of brackish groundwater from the down-dip sections will require relatively deep production wells. In addition, elevated concentrations of radium and radon also occur in the Ellenburger-San Saba aquifer as it occurs in the underlying Hickory, and this would have to be addressed if this aquifer is considered as a brackish water resource.

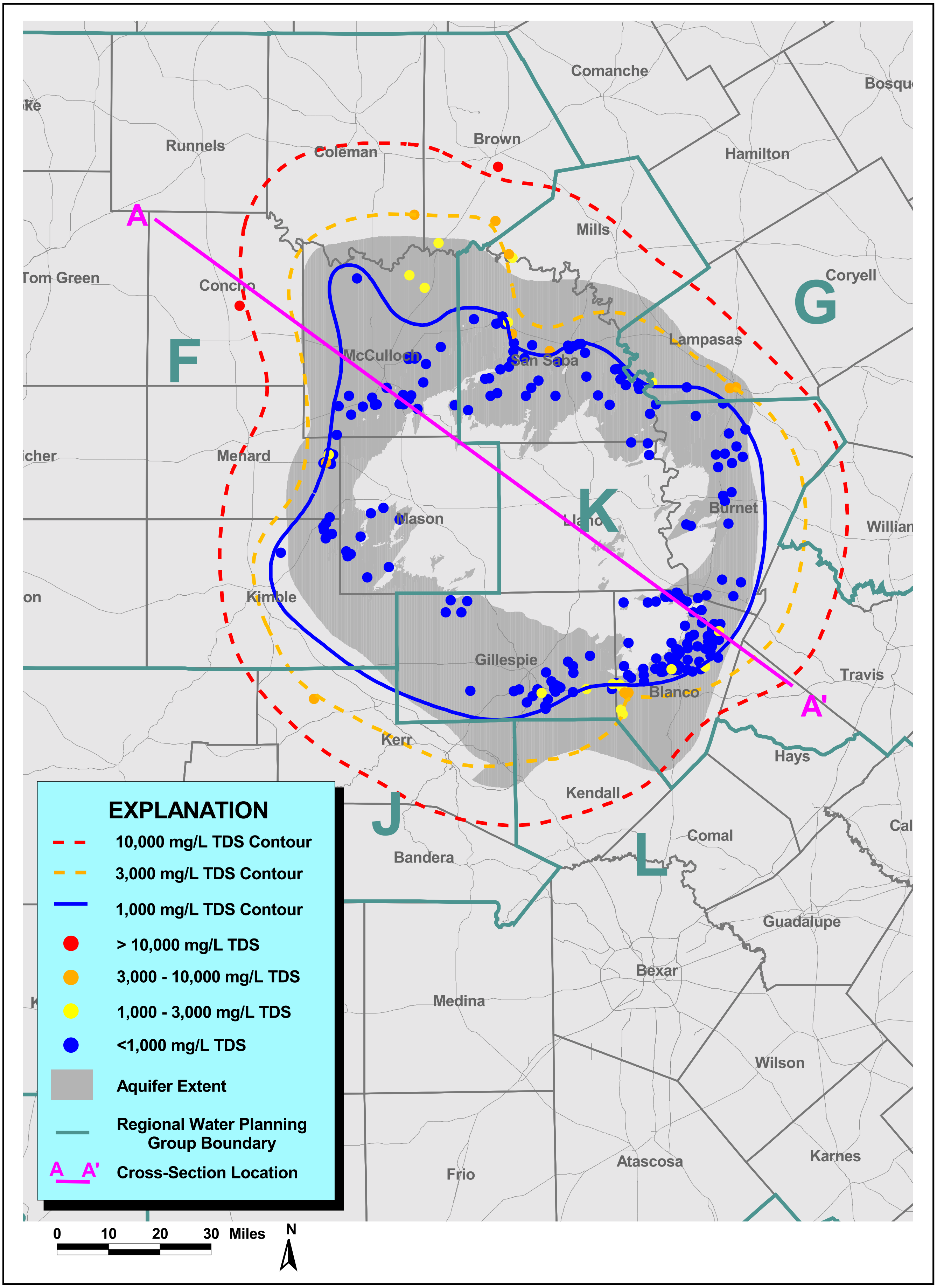
As noted above, the Ellenburger Formation may also provide a brackish groundwater resource beyond the extent of the aquifer in Central Texas. The Ellenburger is present extensively throughout West Texas, and is often used as a source of water for secondary recovery operations.

Availability- LOW to MODERATE- In many of the regions included in the table below, very little of the aquifer is present. Where substantial portions of the Ellenburger-San Saba aquifer are present, low to moderate availability is expected.

Productivity- MODERATE- Due to lower transmissivities, the productivity of the Ellenburger-San Saba aquifer is only moderate.

Source Water Production Cost- MODERATE to HIGH- The deep nature of the Ellenburger-San Saba aquifer in Central Texas, combined with the moderate yields that can be expected from wells, make the relative production cost from the aquifer moderate to high.

Summary of Brackish Water In the Ellenburger-San Saba Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
F- Region F	Moderate	Moderate	Moderate to High
G- Brazos	Low	Moderate	Moderate
J- Plateau	Low	Moderate	High
K- Lower Colorado	Moderate	Moderate	Moderate to High
L- South Central Texas	Low	Moderate	High



GROUNDWATER QUALITY IN THE ELLENBURGER-SAN SABA AQUIFER

FIGURE 53

LBG-GUYTON ASSOCIATES

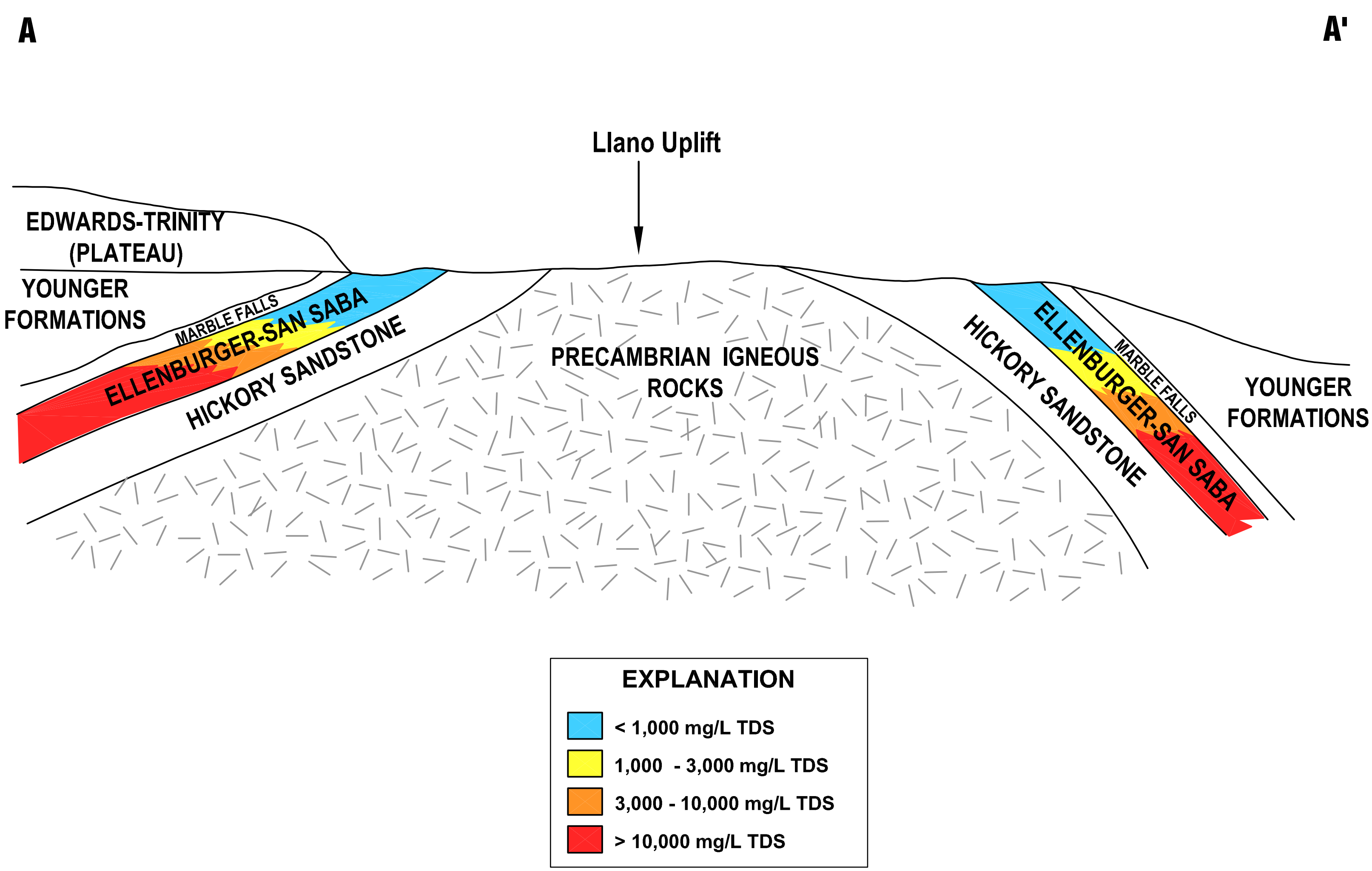


FIGURE 54

SIMPLIFIED CROSS SECTION OF THE ELLENBURGER-SAN SABA AQUIFER WITH GENERALIZED WATER QUALITY RANGES

(Modified from Barker and others, 1994)

LBG-GUYTON ASSOCIATES

3.2.15 Marble Falls

The Marble Falls aquifer is a limestone aquifer that occurs in 8 counties in the Llano Uplift area in Central Texas, as shown in Figure 55. Groundwater from the Marble Falls aquifer is currently used mostly for livestock purposes, although small amounts are also used for municipal purposes. The towns of San Saba and Rochelle are the two largest communities that have historically withdrawn groundwater from the Marble Falls aquifer for public supply use. Most of the production from the Marble Falls aquifer occurs in Mason County.

A generic cross section of the Marble Falls aquifer is shown in Figure 56. The Marble Falls Formation is a Pennsylvanian age, fine-grained, thinly to thickly bedded limestone, with some interbedded shale. It occurs in several separate outcrops, primarily along the northern and eastern flanks of the Llano Uplift region where it reaches a thickness of up to 600 feet. The down-dip extent of the aquifer has not been explored.

Recharge to the Marble Falls aquifer is from precipitation on the outcrop areas. Discharge is mainly to numerous large springs emanating from the aquifer, and to wells. Groundwater flow is generally from the outcrop areas in a down-dip direction. Groundwater occurs in solution cavities that have formed along fractures and faults in the limestone. Where underlying beds are thin or absent, the Marble Falls and Ellenburger-San Saba aquifers may be hydrologically connected. The aquifer is capable of producing small to moderate quantities of water to wells, with well yields increasing significantly with acidizing. Wells completed in the Marble Falls aquifer generally produce less than 100 gpm, although some irrigation wells have been reported to produce as much as 200 gpm. Very few data exist on the overall aquifer characteristics of the Marble Falls aquifer. However, based on well yields and aquifer characteristics of similar aquifers, transmissivities are estimated to average less than 5,000 gpd/ft, storage coefficients are estimated to average 1×10^{-4}, and specific yields are estimated to average 0.02.

As indicated in Figure 55, existing data for the Marble Falls aquifer show that it contains mostly fresh water in outcrop areas and becomes mineralized a short distance down-dip from the outcrop areas. However, very few data exist to evaluate the brackish water that is present.

Summary

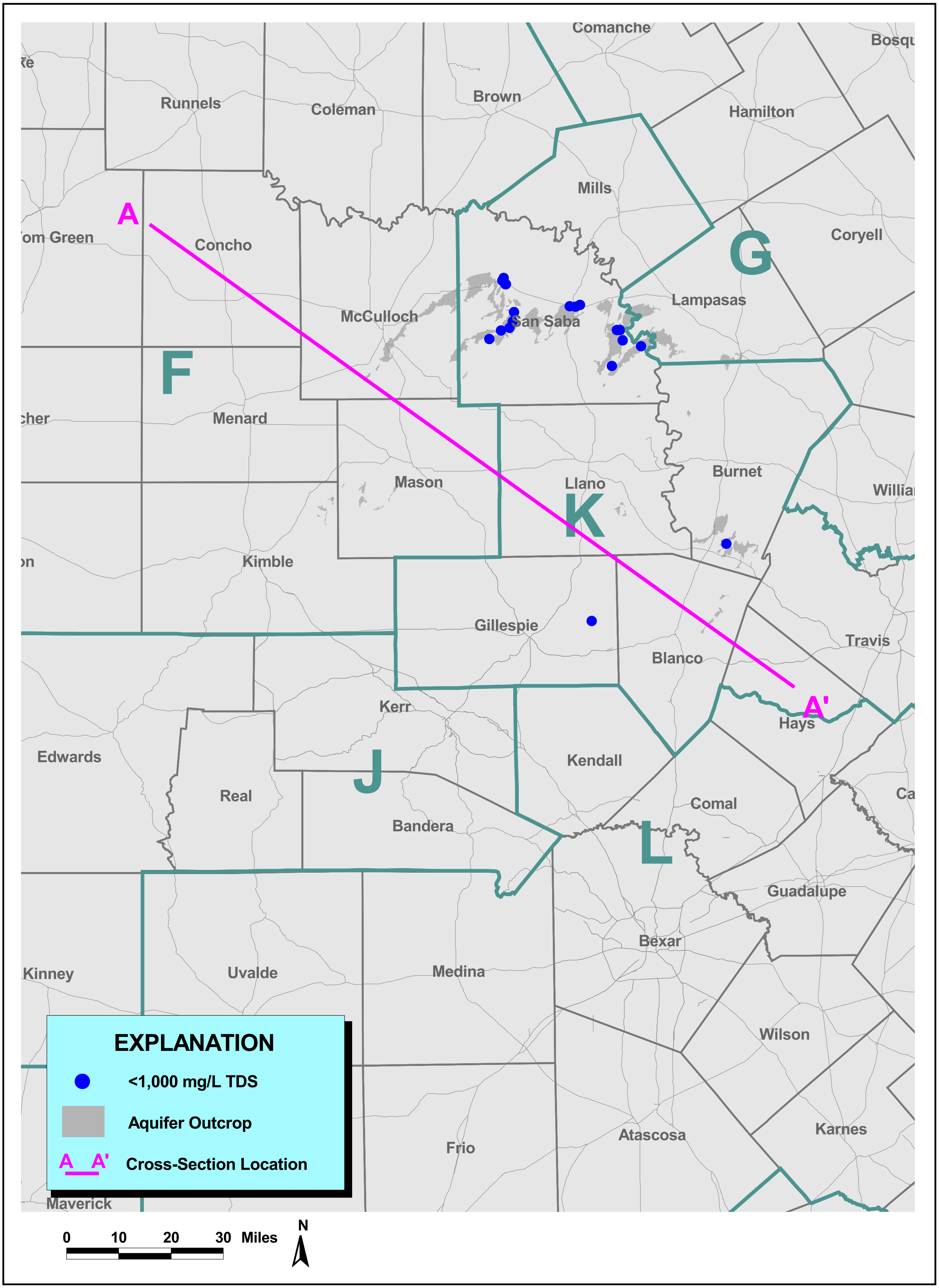
Most wells producing from the Marble Falls aquifer produce fresh groundwater on the outcrop, while groundwater becomes highly mineralized within a relatively short distance of the down-dip. However, because the areal extent of the Marble Falls aquifer is relatively limited, and because much of the existing data indicate that the aquifer has limited groundwater availability, the Marble Falls aquifer must be considered a very limited source of brackish groundwater.

Availability- LOW- The limited overall extent of the aquifer makes it a poor candidate as a brackish water source.

Productivity- UNKNOWN- The aquifer characteristics of the Marble Falls in the down-dip areas where brackish groundwater may be available are unknown.

Source Water Production Cost- MODERATE to HIGH- Due to the presumed deep nature where brackish groundwater would be located, and the low productivity of the aquifer, relative costs are expected to be moderate to high.

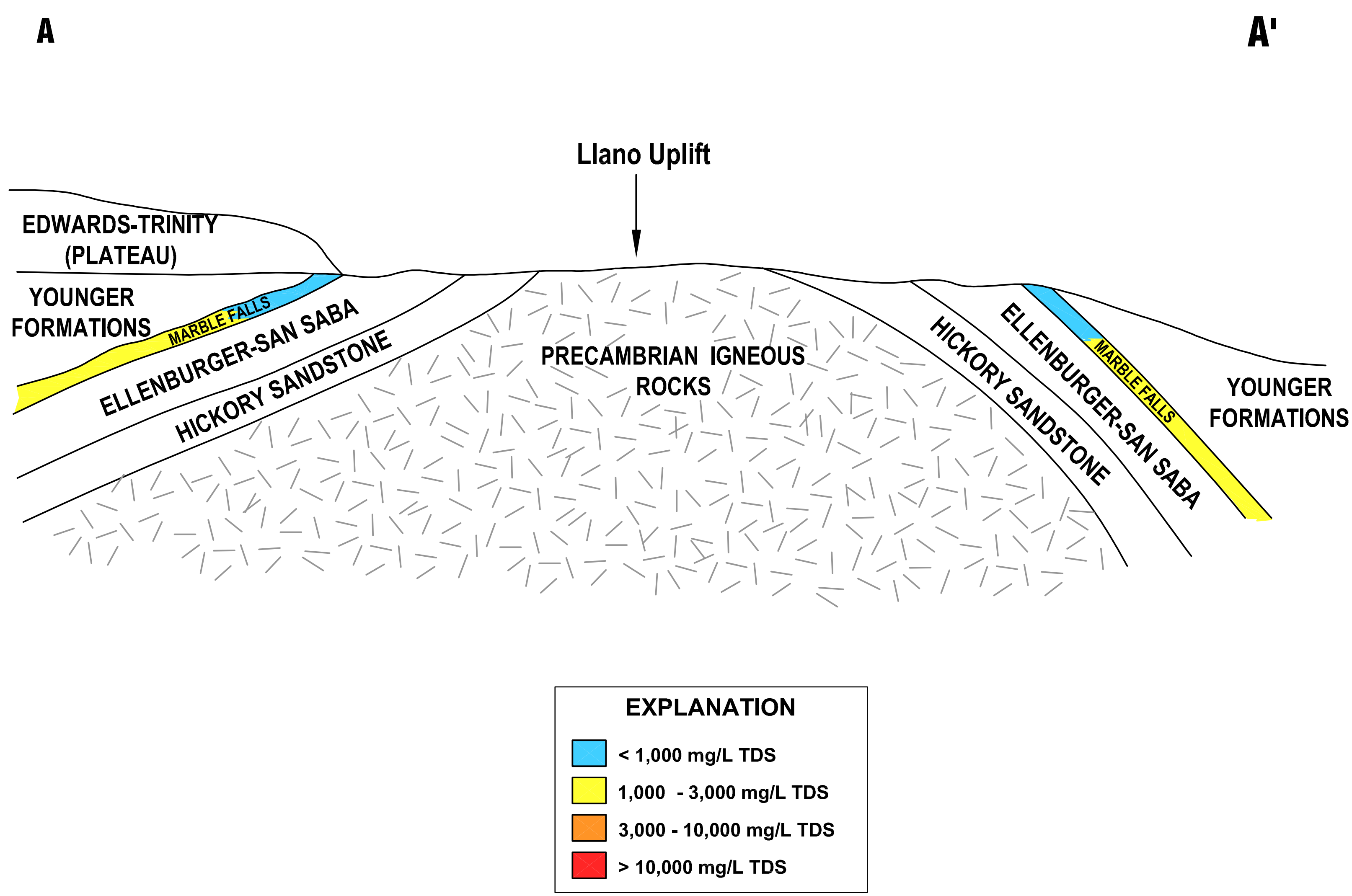
Summary of Brackish Water In the Marble Falls Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
F- Region F	Low	Unknown	Moderate to High
G- Brazos	Low	Unknown	Moderate to High
J- Plateau	Low	Unknown	Moderate to High
K- Lower Colorado	Low	Unknown	Moderate to High
L- South Central Texas	Low	Unknown	Moderate to High



GROUNDWATER QUALITY IN THE MARBLE FALLS AQUIFER

FIGURE 55

LBG-GUYTON ASSOCIATES



SIMPLIFIED CROSS SECTION OF THE MARBLE FALLS AQUIFER WITH GENERALIZED WATER QUALITY RANGES
(Modified from Barker and others, 1994)

FIGURE 56

LBG-GUYTON ASSOCIATES

3.2.16 Woodbine

The Woodbine aquifer is a Cretaceous age sandstone aquifer that extends from McLennan County in North-Central Texas to the Oklahoma-Texas border along the Red River, as shown in Figure 57. The Woodbine is extensively used for irrigation, domestic and stock, and municipal and industrial purposes. Municipal use accounts for the largest percentage of water use from the Woodbine.

The Woodbine Formation is composed of water-bearing sandstone beds interbedded with shale and clay. A cross section of the Woodbine aquifer is shown in Figure 58. The aquifer outcrops at its western extent and dips eastward to depths of over 2,500 feet below land surface with a thickness of about 700 feet. In the northern portions of the aquifer, the Woodbine is often divided into three sections, referred to as the "Upper", "Middle", and "Lower" Woodbine. The Lower Woodbine yields the most water of the three, and the Upper Woodbine yields limited quantities of water that is very high in iron.

Groundwater is found in the Woodbine under both water-table and artesian conditions. Water-table conditions occur in the outcrop areas, and quickly become confined down-dip. Hydraulic gradients range from less than 13 feet/mile to over 30 feet/mile, with an average reported velocity of 15 feet/year[1]. Wells completed into the Woodbine can yield moderate to large quantities of water, with reported capacities of up to 1,000 gpm. Average yields tend to be between 100 and 300 gpm throughout the extent of the Woodbine, with specific capacities ranging between 1 and 10 gpm/ft. Artesian storage coefficients in the Woodbine have been estimated to be about 1.5×10^{-4}, and transmissivities range from 1,000 to over 15,000 gpd/ft[1]. Specific yields near the outcrop areas are estimated to be 0.10 to 0.15. Groundwater has been produced from the Woodbine for many years, and in areas of high production, long-term water-level declines have been observed. Recharge to the Woodbine is primarily from the infiltration of precipitation on the outcrop, and estimates of less than one inch/year of recharge have been made[1]. Discharge from the Woodbine is to pumpage from wells.

Water quality deteriorates with depth throughout the Woodbine, most notably below 1,000 feet. Some shallow zones in and near the outcrop contain groundwater over 3,000 mg/L TDS, although as shown in Figure 57, these areas are sporadic. These zones are usually cased off for fresh water production wells, but could be tapped for brackish water production. Existing water-quality data were used to estimate the location of 1,000 and 3,000 mg/L TDS contour lines, however, the 10,000 mg/L TDS contour line was based mainly on previous work[2].

Summary

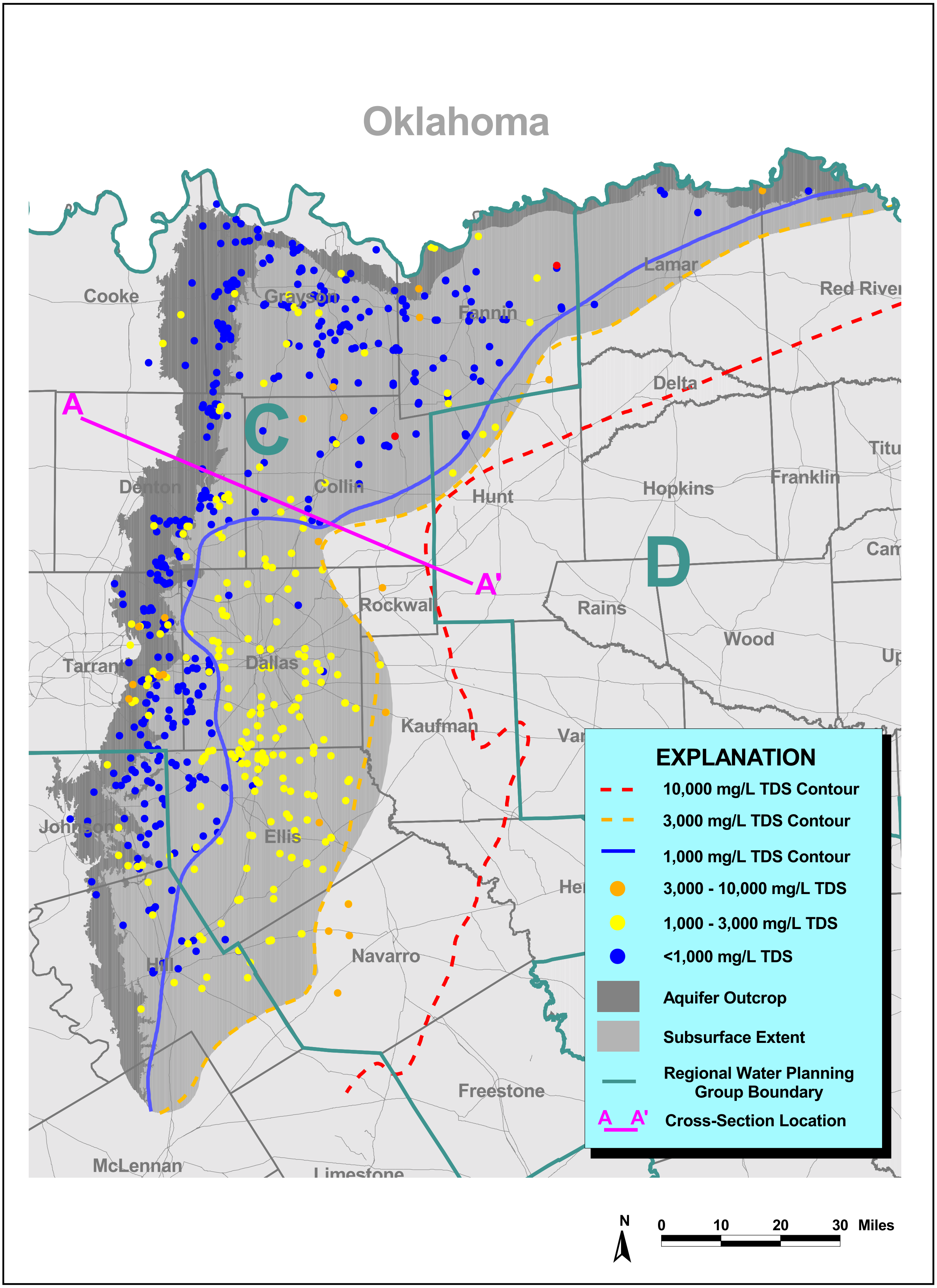
The Woodbine aquifer contains extensive brackish groundwater resources. In some areas poorer quality water is found in the outcrop areas, in particular from the "Upper" Woodbine. However, the main source of brackish water from the Woodbine appears to be from the down-dip sections where water quality deteriorates. The Woodbine has the capability of producing moderate to large quantities of water to wells, and the down-dip areas, where water quality is consistently poor, has the potential to be a good source of brackish water.

Availability- LOW to HIGH- Where the Woodbine is present, mainly in Region C, it may provide good availability for the region for brackish groundwater.

Productivity- LOW to MODERATE- The Woodbine aquifer tends to be significantly less transmissive in the down-dip areas where brackish groundwater is typically encountered.

Source Water Production Cost- MODERATE to HIGH- Due to the tighter and deeper nature of the aquifer in the areas where brackish groundwater is typically encountered, production costs are expected to be moderate to high.

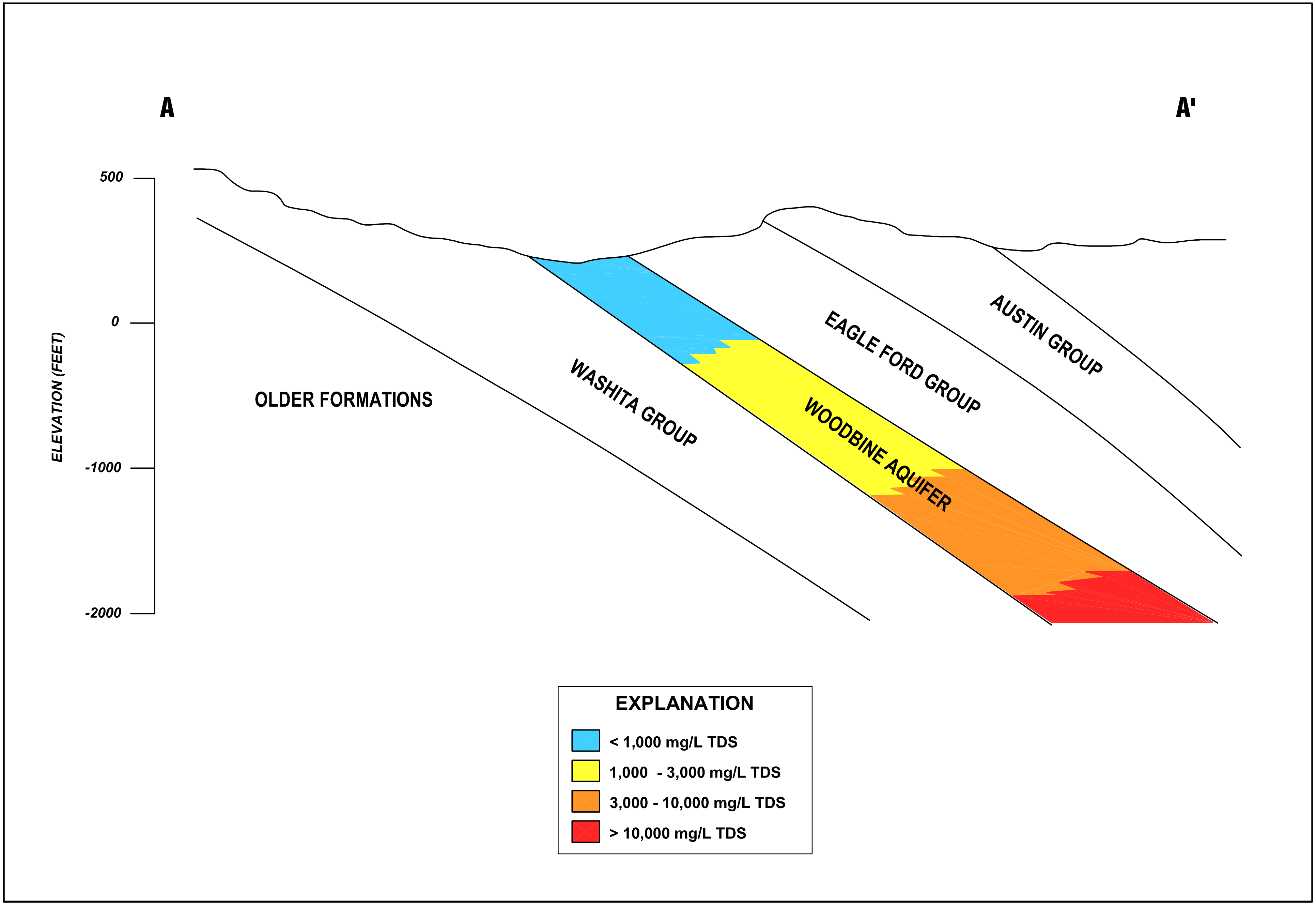
Summary of Brackish Water In the Woodbine Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
C- Region C	High	Low to Moderate	Moderate to High
D- North East Texas	Low	Low to Moderate	Moderate to High
G- Brazos	Moderate	Low to Moderate	Moderate to High



GROUNDWATER QUALITY IN THE WOODBINE AQUIFER

FIGURE 57

LBG-GUYTON ASSOCIATES



SIMPLIFIED CROSS SECTION OF THE WOODBINE AQUIFER WITH GENERALIZED WATER QUALITY RANGES

(Modified from Ashworth, 1995)

FIGURE 58

LBG-GUYTON ASSOCIATES

3.2.17 Blossom

The Blossom is a Cretaceous age sandstone aquifer that is found in parts of Bowie, Red River, and Lamar Counties in the northeast corner of Texas, as shown in Figure 59. Most of the groundwater produced from the Blossom is currently used for rural domestic purposes. Historically, the City of Clarksville was the largest user of Blossom groundwater.

A schematic cross section of the Blossom aquifer is shown in Figure 60. The Blossom Sand Formation consists of discontinuous sand beds with interbedded layers of shale, clay, marl, and chalk. In places, the formation attains a thickness of 400 feet, although generally less than 30 percent of this thickness consists of water-bearing sand[1]. The aquifer yields small to moderate quantities of water over a limited area on and south of the outcrop. The largest Blossom well yields are 650 gpm, which occur in Red River County. Production decreases in the western half of the aquifer, where yields of 35 gpm to 85 gpm are more typical. Only a limited number of aquifer tests have been conducted on the Blossom aquifer. The few tests that have been conducted indicate that transmissivities range from 600 to 4,000 gpd/ft, artesian storage coefficients range from 3×10^{-5} to 7×10^{-5}, and specific yields in the outcrop range from 0.10 to 0.20. An average porosity of 37% for the sand intervals was determined in TWDB test holes[1]. Water-level declines have occurred in the past in areas where the aquifer is heavily used, but the rate of decline has slowed in some areas because an increased use of surface-water has reduced groundwater pumpage.

Groundwater from the Blossom aquifer is generally slightly-alkaline, and, in some areas, high in sodium, bicarbonate, and iron. Very little groundwater-quality data are available in the down-dip portions of the Blossom. Water samples from one down-dip well in Lamar County contain TDS concentrations over 16,000 mg/L. The location of this well suggests that the transition from fresh to saline groundwater occurs over a distance of about 3 miles. Due to lack of data for other portions of the down-dip section, it is assumed that this relatively quick transition occurs throughout the Blossom aquifer and that is the basis for the 10,000 mg/L TDS contour line location shown in Figure 59.

Summary

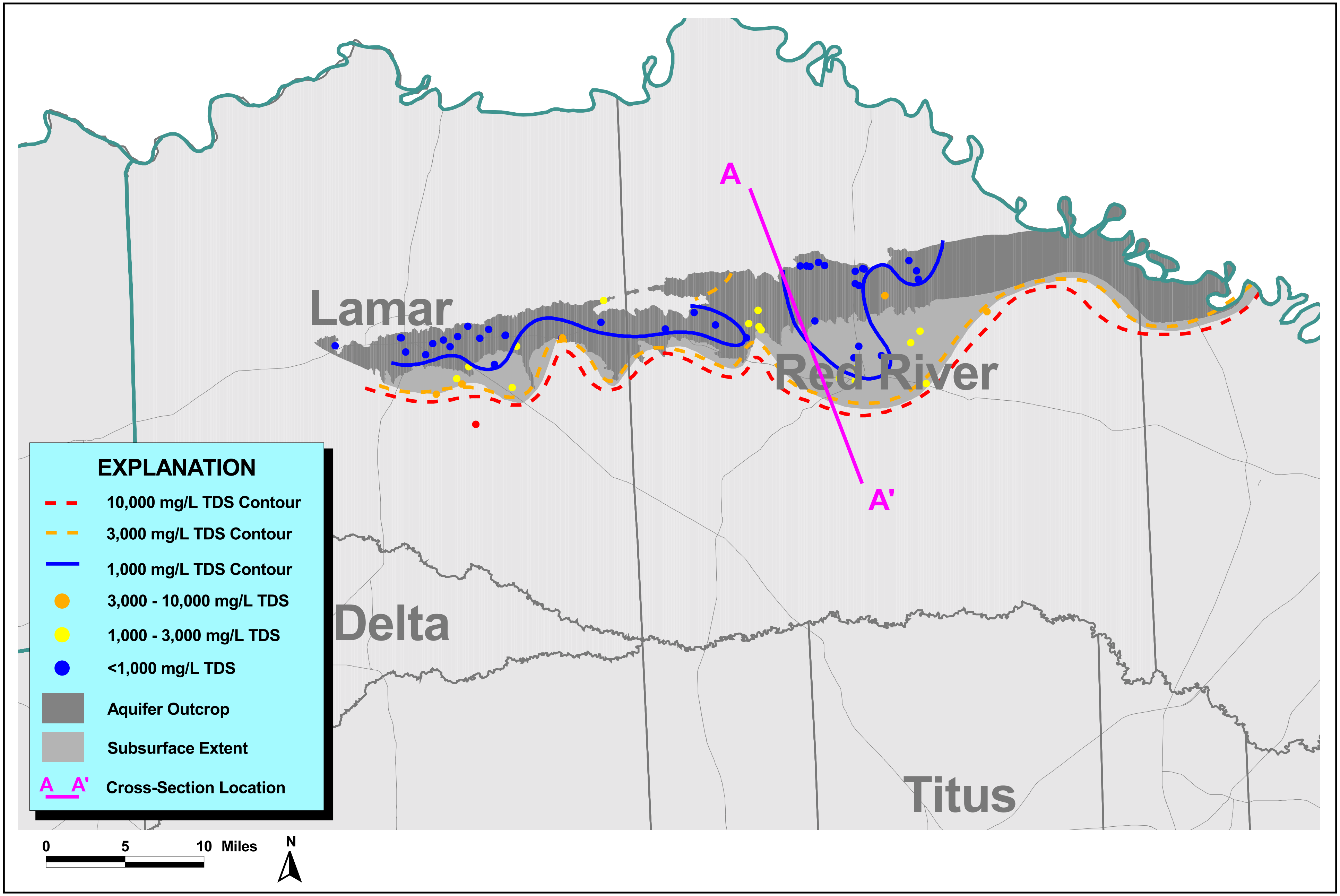
The Blossom aquifer may serve as a limited source of brackish water; however, its overall potential is poor. Well yields and production from the Blossom are limited, and the apparent rapid transition from fresh to saline water does not result in a significant potential for brackish water supplies. Therefore, the aquifer should be considered as a brackish water resource only for relatively small water demands if other sources are not available.

Availability- LOW- The Blossom aquifer is very limited in extent and contains relatively little water of any type. The rapid transition from fresh to saline groundwater leaves a very limited brackish groundwater resource.

Productivity- LOW- The availability is low, the areas where brackish groundwater is found is limited, and the aquifer generally yields low quantities of groundwater.

Source Water Production Cost- MODERATE- Relatively low production yields, a thin production zone within the aquifer, and the increased depths that brackish groundwater may be encountered results in moderate costs to produce brackish groundwater from the Blossom aquifer.

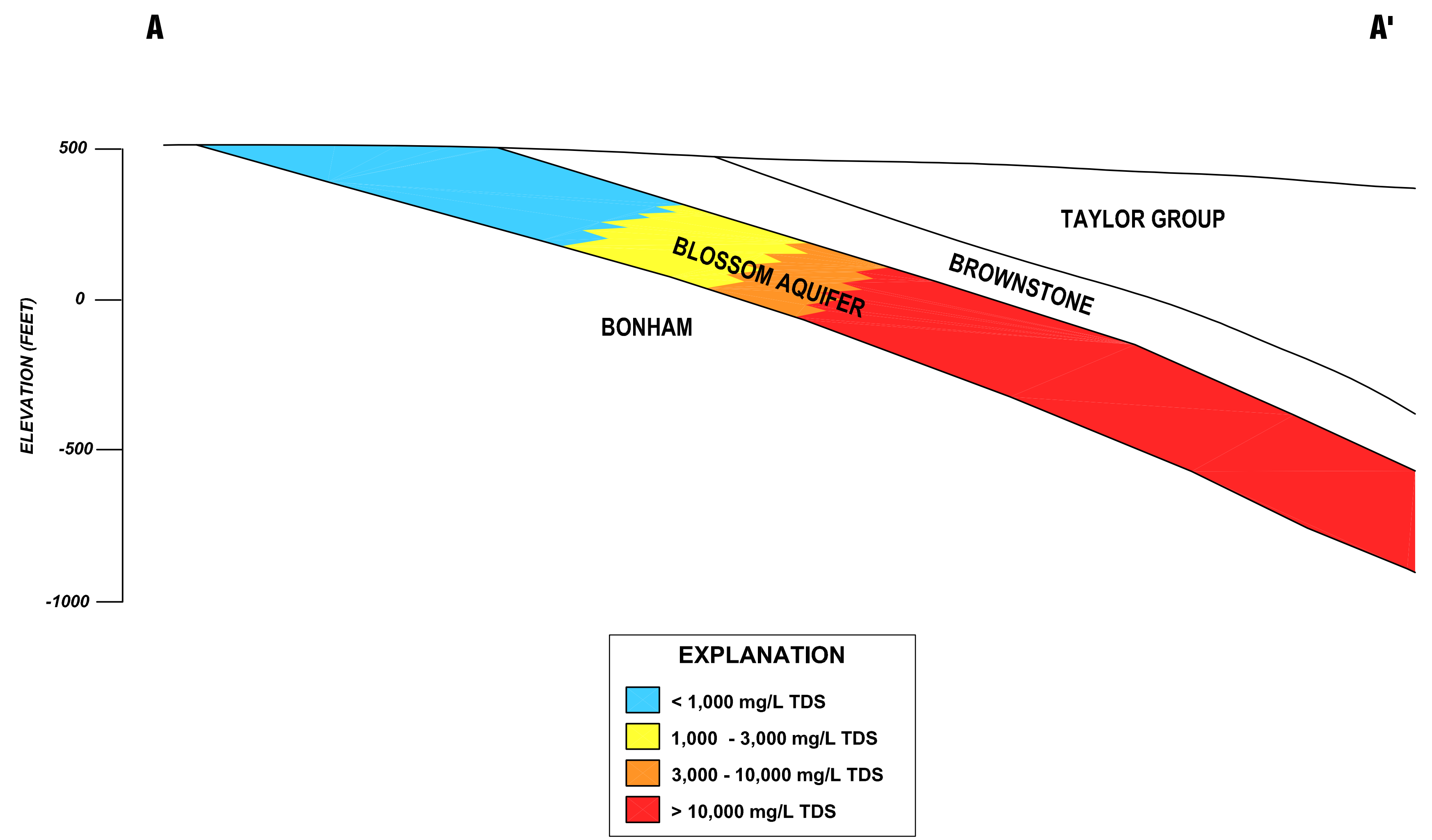
Summary of Brackish Water In the Blossom Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
D- North East Texas	Low	Low	Moderate



GROUNDWATER QUALITY IN THE
BLOSSOM AQUIFER

FIGURE 59

LBG-GUYTON ASSOCIATES



SIMPLIFIED CROSS SECTION OF THE BLOSSOM AQUIFER WITH GENERALIZED WATER QUALITY RANGES
(Modified from McLaurin, 1972)

FIGURE 60

LBG-GUYTON ASSOCIATES

3.2.18 Nacatoch

The Nacatoch is a Cretaceous age sandstone aquifer that occurs in a narrow band in Northeast Texas and extends eastward into Arkansas and Louisiana, as shown in Figure 61. Groundwater produced from the Nacatoch is used for irrigation, industrial, municipal, domestic, and livestock purposes, of which municipal and industrial account for the largest percentage.

The Nacatoch is composed of sequences of sand beds separated by impermeable layers of mudstone or clay. A schematic cross section of the Nacatoch is shown in Figure 62. These mudstone/clay layers prevent the mixing of waters from the different producing zones, and therefore each sand unit is a separate hydrologic unit. In the subsurface, the confined sections of the aquifer dip to the south and east, however these dipping beds are interrupted by the Mexia-Talco fault system, which diverts or stops the normal down-dip flow of groundwater in the formation. A limited number of wells have been tested from the Nacatoch, and based on these data it is estimated that transmissivities range from about 1,500 to nearly 15,000 gpd/ft, with specific capacities of between 1 and 14 gpm/ft. Storage coefficients are estimated to average approximately 1×10^{-4} to 1×10^{-5} and specific yields near the outcrop are estimated to be 0.10 to 0.20. Well yields can be as high as 300 gpm.

Fresh groundwater is generally found in the Nacatoch in the outcrop area and slightly down-dip, as shown in Figure 61. As noted above, the Mexia-Talco fault zone interrupts the normal down-dip flow of groundwater, and so the 3,000 mg/L line is generally controlled by this structural feature. The overall quality of groundwater in the aquifer is generally alkaline, high in sodium bicarbonate. In areas where the Nacatoch occurs as multiple sand layers, the upper sand layer contains the best-quality water.

Summary

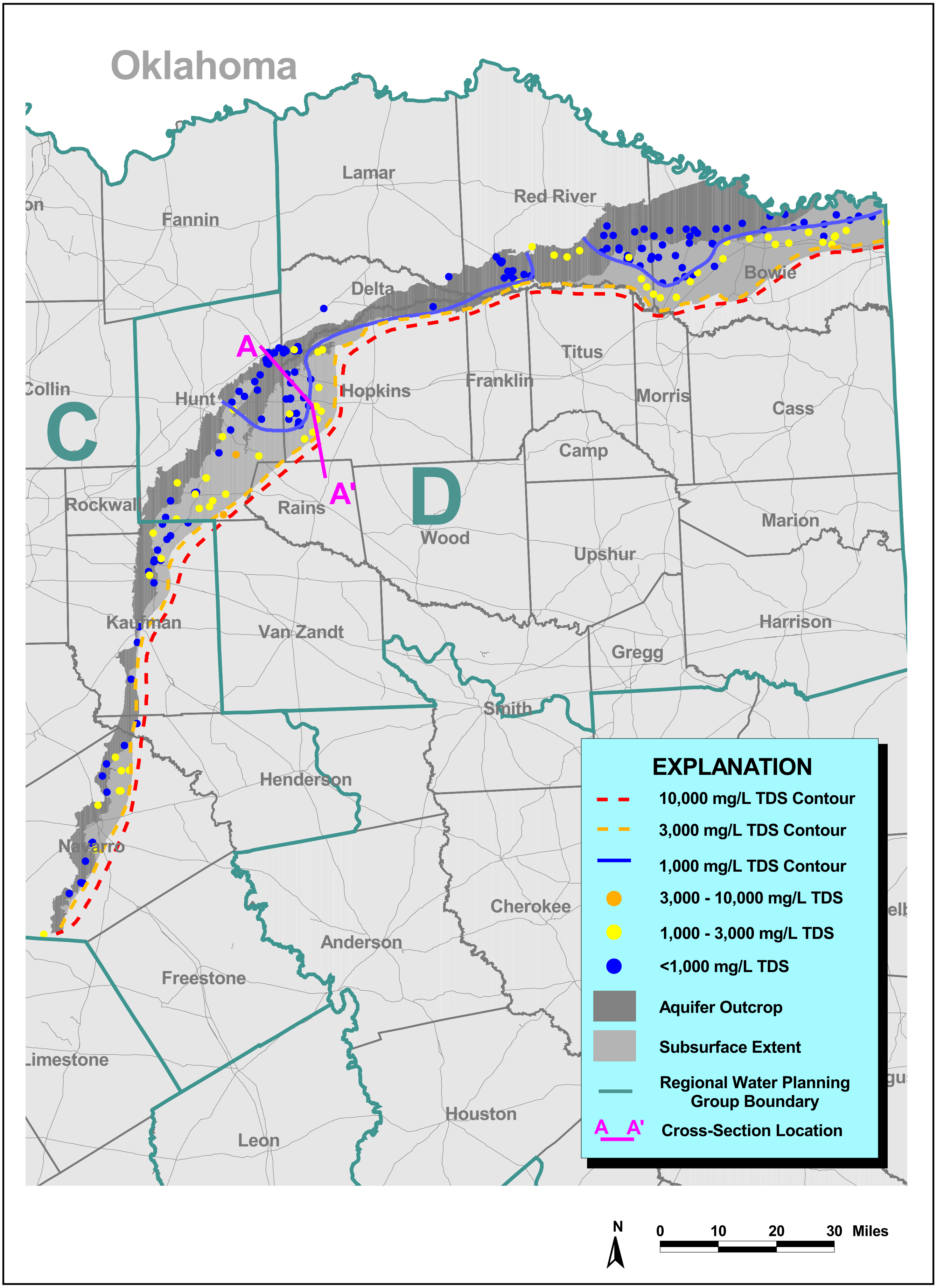
Much of the groundwater in the Nacatoch that is down-dip from the outcrop appears brackish. However, the transition zone from fresh to saline groundwater is very small, resulting in a very limited brackish resource. The Nacatoch aquifer should therefore be considered a poor source of brackish groundwater.

Availability- LOW to MODERATE- Because of the sporadic occurrence of brackish groundwater in and near the outcrop areas of the Nacatoch aquifer, and the quick transition from fresh to saline groundwater in the down-dip portions of the aqufier, availability of brackish groundwater from the Nacatoch must be considered low to moderate. Availability is significantly less in the southern (Kaufman and Navarro Counties) area.

Productivity- LOW- Due to the very limited extent of brackish groundwater in the Nacatoch, and the increasing depth and tighter nature of the aquifer in the brackish sections, the productivity is considered to be low.

Source Water Production Cost- MODERATE to HIGH- The aquifer tends to be less transmissive and deeper where brackish groundwater is found. This will result in wells that are more expensive to install, resulting in relatively high costs.

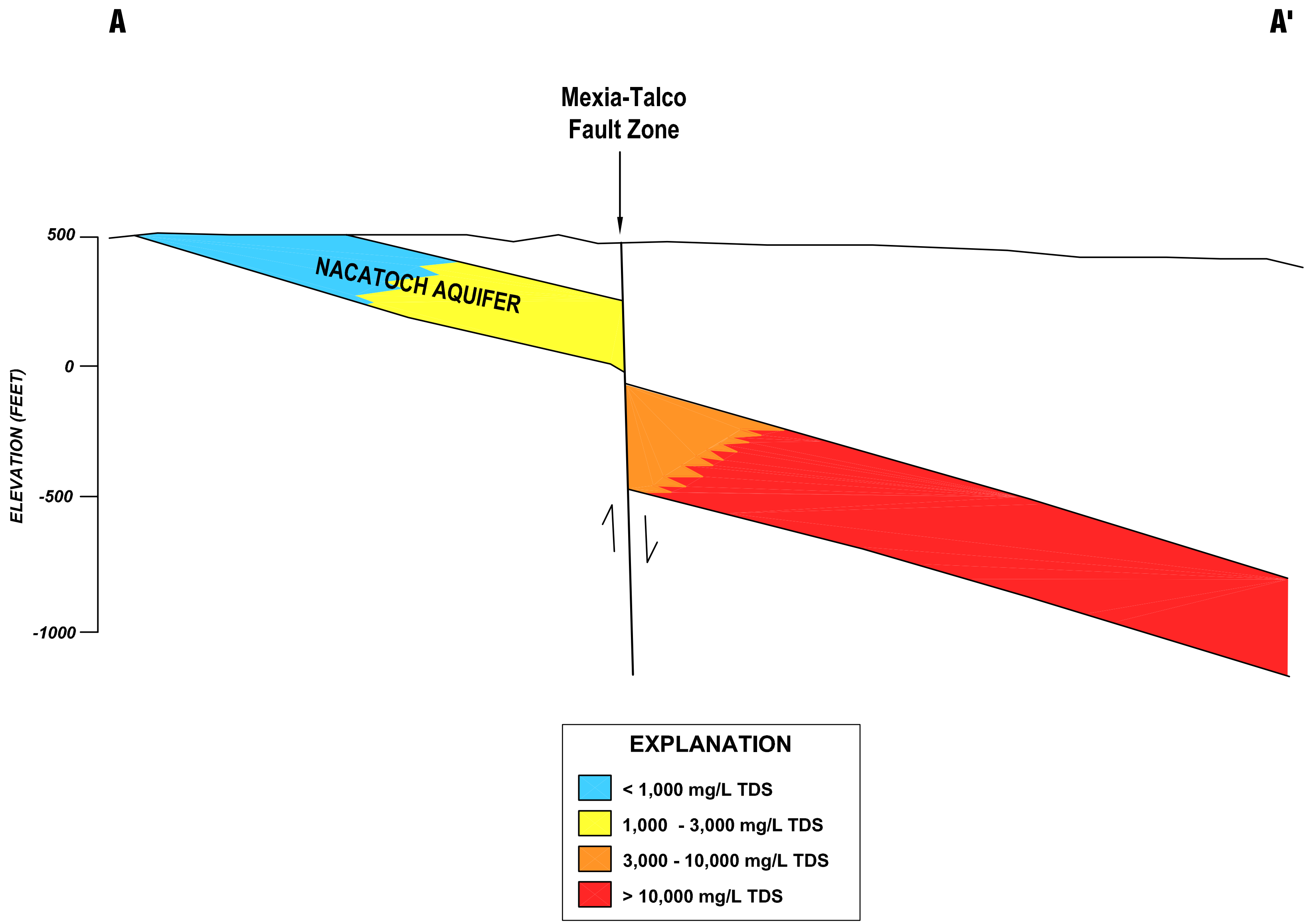
Summary of Brackish Water In the Nacatoch Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
C- Region C	Low	Low	Moderate to High
D- North East Texas	Low to Moderate	Low	Moderate



GROUNDWATER QUALITY IN THE NACATOCH AQUIFER

FIGURE 61

LBG-GUYTON ASSOCIATES



SIMPLIFIED CROSS SECTION OF THE NACATOCH AQUIFER WITH GENERALIZED WATER QUALITY RANGES
(Modified from Ashworth, 2002)

FIGURE 62

LBG-GUYTON ASSOCIATES

3.2.19 Queen City and Sparta

The Queen City and Sparta are Tertiary age sand aquifers that extend from the Rio Grande in south Texas northeastward to the Louisiana border, as shown in Figure 63. Groundwater is currently produced from the entire extent of the aquifer and is used for municipal, industrial, irrigation, domestic, and livestock purposes. The Queen City and Sparta aquifers are considered by the TWDB to be separate minor aquifers. However, in the down-dip portions of these aquifers, where most of the brackish groundwater is found, these formations become thicker, lose much of their sand content, and become difficult to differentiate from the Weches Formation that separates them. For these reasons, they are described together in this report.

The outcrop of the Queen City and Sparta aquifers consists of the surface areas of the Queen City Sand, the Weches Formation, and the Sparta Sand throughout most of their extent. West and southwest of the Frio River, however, the outcrop consists of the Bigford, El Pico, and Laredo Formations. A general cross section of the Queen City and Sparta aquifers is shown in Figure 64. Both aquifers consist principally of thin to massive sand and sandstone beds, with some interbedded clays and silts. Thicknesses generally range from about 500 to over 3,000 feet, and the water-bearing sands of these aquifers generally dip to the south and southeast towards the coast. The thickest and highest percentage of sand units in these aquifers occurs near the outcrop. However, these sands tend to pinch out in the down-dip direction from the outcrop where they are replaced by clay, silt, and shale units.

Recharge to the Queen City and Sparta aquifers is through the infiltration of precipitation on the outcrop. Groundwater moves down-dip, as well as to rivers and streams in the outcrop area. Discharge is to wells producing from the aquifer. These aquifers yield small to large quantities of fresh groundwater to wells in and near the outcrop. Transmissivities of these aquifers range from about 2,000 to 20,000 gpd/ft and generally decrease away from the outcrop. Storage coefficients range from 1×10^{-3} to 1×10^{-4}, with specific capacities generally less than 10 gpm/ft. Specific yields near the outcrop are estimated to be 0.20. Wells in and near the outcrops will typically produce between 200 and 500 gpm, although larger capacity wells may be possible in some areas.

In general, fresh groundwater is found in the outcrop portion of the Queen City and Sparta aquifers in most of the state, although some slightly-saline water is present in the outcrop areas in Central Texas. In South Texas, virtually no fresh water is present, even in the outcrop areas. The TDS of groundwater in the Queen City and Sparta aquifers typically increases rapidly as the aquifer increases in depth, and saline water with greater than 10,000 mg/L TDS is found in some areas relatively close to the outcrop.

Summary

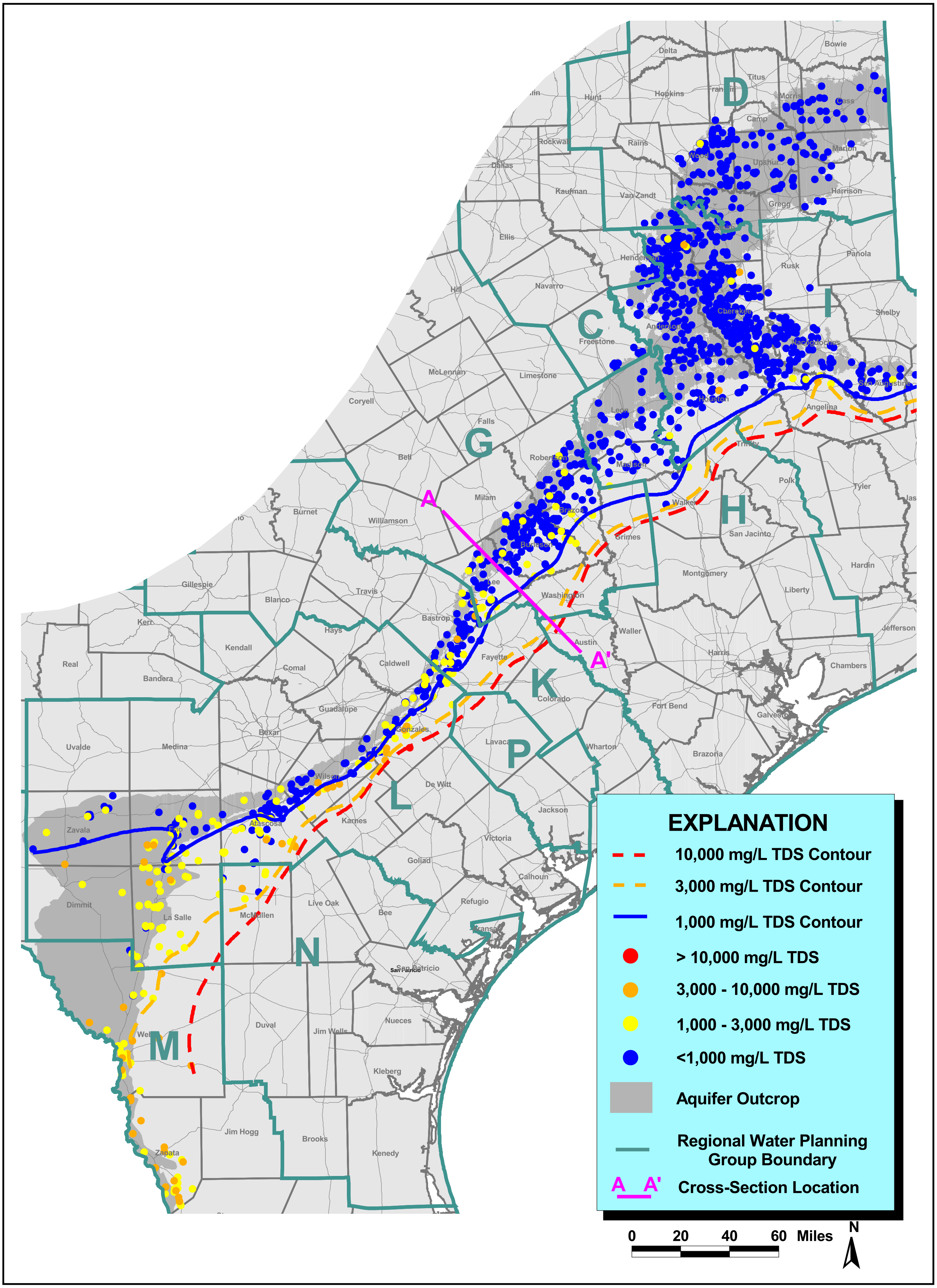
The down-dip portion of the Queen City and Sparta aquifers contains a potential brackish groundwater resource. In South Texas, even the outcrop area of these aquifers should be considered a potential brackish water resource, as in this area little or no fresh water is found. In most of the extent of these aquifers, the depths of wells that generally produce fresh groundwater are usually 1,000 feet deep or less, and wells producing slightly- to moderately-saline groundwater range in depth from 1,000 to 2,500 feet. These depths and the lower productivity expected in the down-dip, brackish sections of the aquifer, make these aquifers a less practical resource.

Availability- LOW to HIGH- In the down-dip portions of the aquifer, the transmissive sands tend to pinch out, the aquifer tends to get less productive and deeper, and groundwater temperatures increase. In these areas the availability of brackish groundwater is considered to be low. Availability is good in the southern extent of the aquifers, particularly in Regions L and M, where most of the groundwater produced in and near the outcrop is slightly- to moderately-saline. Work done in East Texas indicates that a significant number of wells producing from the Queen City and Sparta aquifers in or near the outcrop produce slightly-saline groundwater. These wells are generally used for irrigation or livestock purposes, but have not been included in the state's water-quality database and so Figure 63 does not reflect the presence of these wells.

Productivity- LOW to MODERATE- Because down-dip resources are the main source of brackish groundwater from the Queen City and Sparta aquifers, and transmissivities in these areas are lower than in the fresh water sections, the productivity is expected to be low to moderate.

Source Water Production Cost- MODERATE to HIGH- Relative production costs are related to the factors described above for availability and productivity. Where brackish groundwater is available in the outcrop areas, production costs should be considered moderate. Where down-dip resources are the main source of brackish groundwater, the production costs will be high due to the deeper and tighter nature of the aquifer in these areas.

Summary of Brackish Water In the Queen City and Sparta Aquifers			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
C- Region C	None	--	--
D- North East Texas	Moderate	Low	Moderate
G- Brazos	Moderate	Low	Moderate to High
H- Region H	Moderate	Low	Moderate to High
I- East Texas	High	Low	Moderate
K- Lower Colorado	Moderate	Low	High
L- South Central Texas	Moderate to High	Low	Moderate to High
M- Rio Grande	High	Moderate	Moderate
N- Coastal Bend	Low	Low	High



GROUNDWATER QUALITY IN THE QUEEN CITY AND SPARTA AQUIFERS

FIGURE 63

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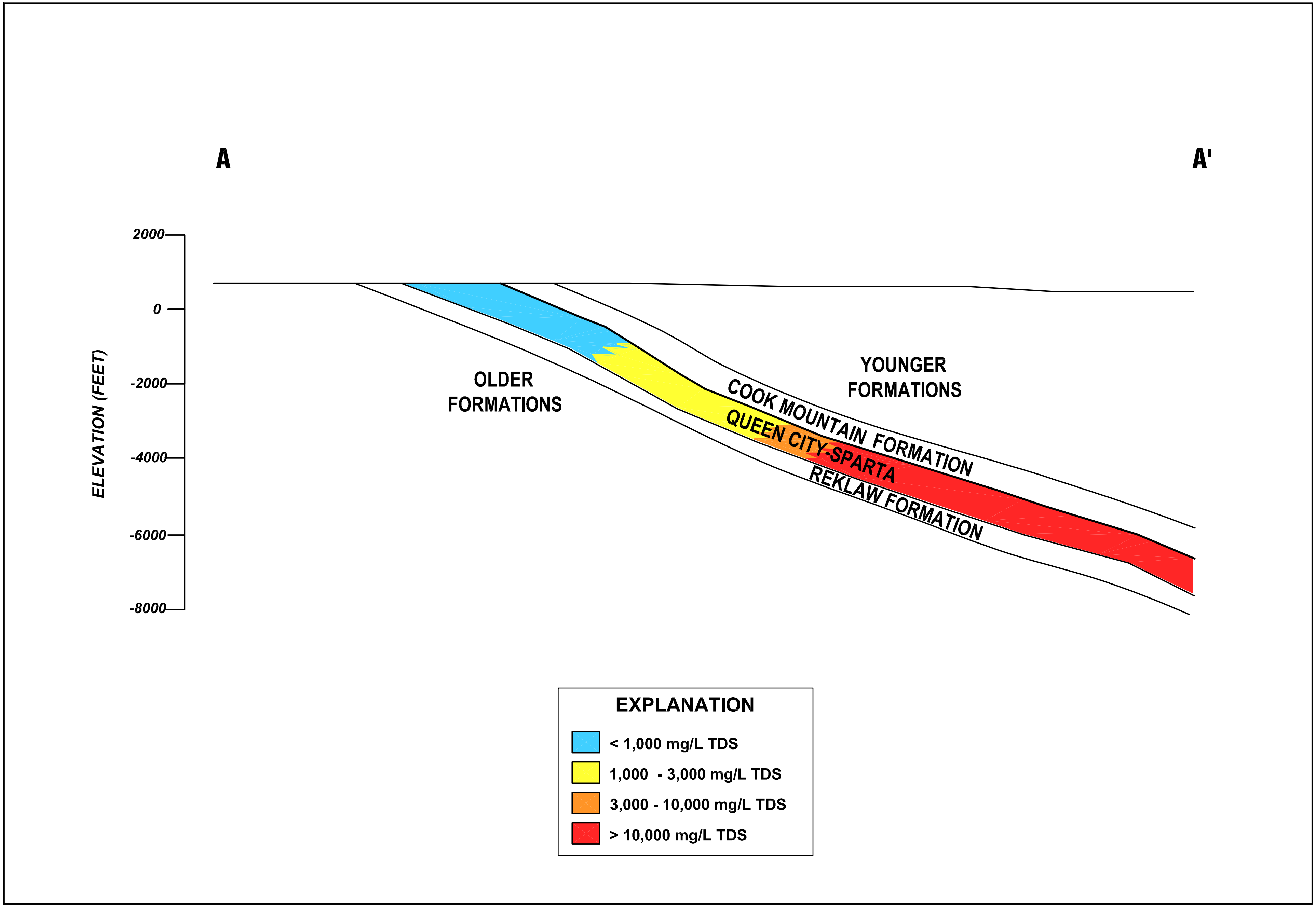


SIMPLIFIED CROSS SECTION OF THE QUEEN CITY AND SPARTA AQUIFERS WITH GENERALIZED WATER QUALITY RANGES

(Modified from Baker, 1995)

FIGURE 64

LBG-GUYTON ASSOCIATES

3.2.20 Yegua-Jackson

The Yegua-Jackson aquifer is a Tertiary age aquifer that extends from the Rio Grande northeastward to the Louisiana border, as shown in Figure 65. These aquifers are mainly used in the northern half of the aquifer extent, and the groundwater produced from these aquifers is used for municipal, industrial, irrigation, domestic, and livestock purposes.

A generalized cross section of the Yegua Formation and Jackson Group is shown in Figure 66. The Yegua Formation consists principally of thin beds of sand, clay, silt with some lignite in the outcrop, and is up to 1,000 feet thick in the fresh to slightly-saline sections of the formation. Individual units within the Yegua Formation are generally not consistent from one area to another, although in many areas a basal sand unit is often the most productive unit within the aquifer. The Yegua thickens significantly in the down-dip direction. Down-dip (south and southeast direction from the outcrop), the sand and sandstone units within the Yegua pinch out in the subsurface. The Jackson Group consists of up to 1,500 feet of mainly clay, lacking many productive sand units, and also thickens significantly in the down-dip direction.

Groundwater is found mainly under artesian conditions in the Yegua-Jackson aquifer. Recharge to these aquifers is through the infiltration of precipitation on the outcrop areas. Groundwater then moves down-dip from the outcrops. Historically, discharge from these aquifers was through the upwards leakage of groundwater to overlying formations. Currently, much of the discharge is to wells.

The Yegua-Jackson aquifer generally yields small to moderate quantities of fresh groundwater to wells near the outcrop. The Yegua tends to be the more productive of the two units, yielding up to 500 gpm to wells. Wells in the Jackson tend to yield less than 50 gpm. The porosity of sandstones and sands of these aquifers probably ranges from about 5 to 20 percent. Transmissivities of these aquifers range from less than 1,000 gpd/ft to 40,000 gpd/ft. Transmissivities in the Jackson are generally much less, though wells producing from some of the few sandy units in the Jackson can have transmissivities up to 14,000 gpd/ft. Storage coefficients may be as high as 1×10^{-3}, and unconfined specific yields are approximately 0.25. Specific capacities for the Yegua range from about 1 gpm/ft to nearly 15 gpm/ft. The average hydraulic conductivity of the sand units is about 20 to 50 gallons per day/ft squared. However, these estimates of transmissivity may be much lower in the down-dip areas where much of the brackish groundwater is present because in these areas the sand units tend to pinch out in the subsurface.

As shown on Figure 65, the groundwater quality in the Yegua-Jackson aquifer varies across its extent. In East Texas, these aquifers contain mostly fresh water in the outcrop areas. In Central Texas the aquifer contains both fresh and slightly-saline water in and near the outcrop. In South Texas even the outcrop areas contain slightly- to moderately-saline groundwater, with little fresh water present. In all areas, groundwater in the aquifer becomes highly mineralized down-dip, although due to the lack of wells producing from these areas, few chemical analytical data are available to illustrate this change. Fresh groundwater is generally found at depths of less than 1,000 feet. Slightly-to moderately-saline groundwater is found at distances of a few miles down-dip from the outcrop at depths on the order of 1,500 feet, although in South Texas slightly- to moderately-saline groundwater is found in the outcrop at depths of generally less than 1,000 feet. Saline groundwater in the Yegua-Jackson aquifer (greater than 10,000 mg/L) is usually found 10 to 15 miles below the outcrop where depths are on the order of 2,500 feet.

Summary

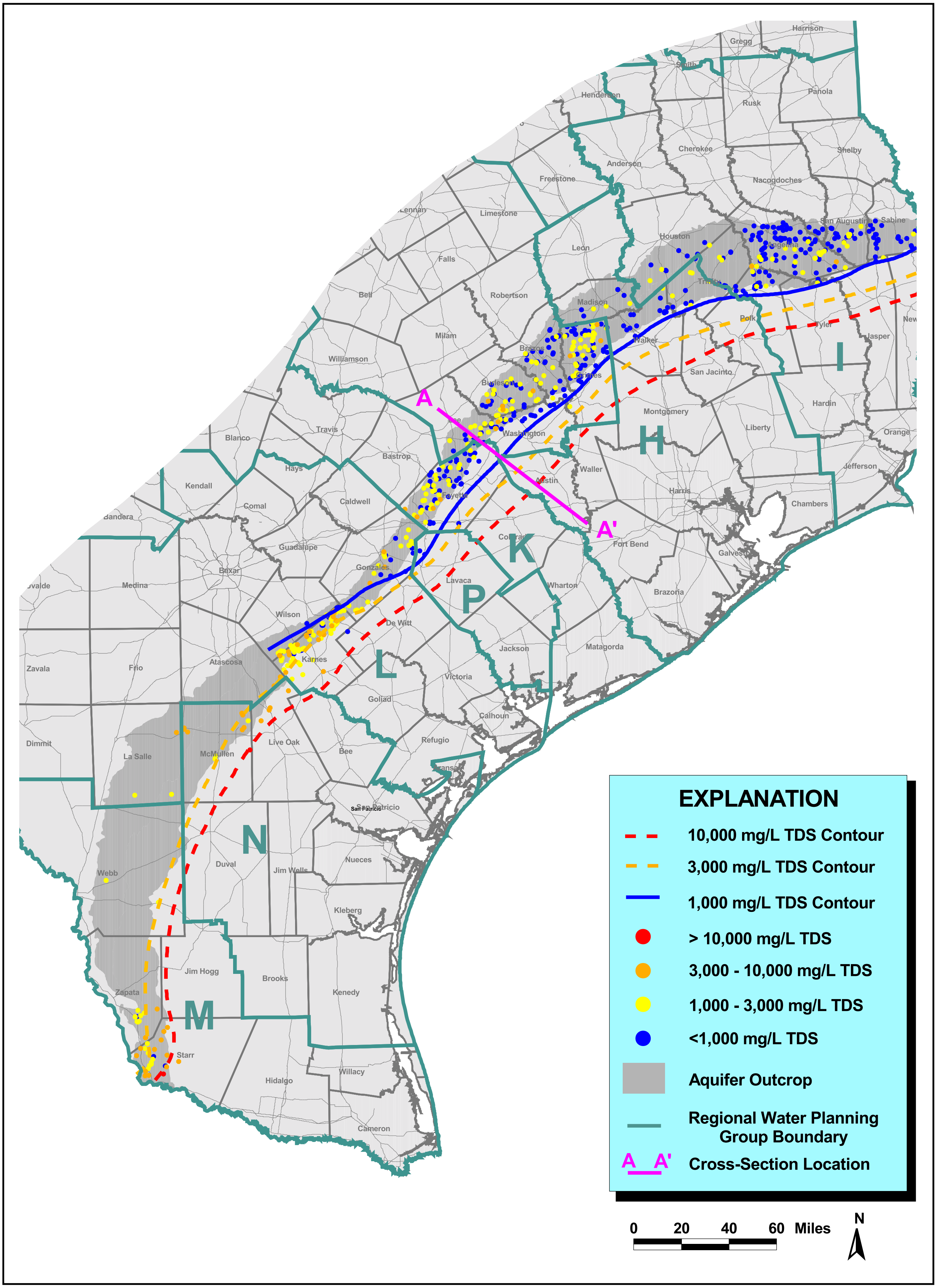
The Yegua-Jackson aquifer may be a source for brackish groundwater in the future. These aquifers contain some slightly- to moderately-saline groundwater in the outcrop areas in Central to South Texas, and groundwater becomes highly mineralized very quickly in the down-dip direction throughout its extent in Texas. The drawbacks to using this aquifer as a source of brackish groundwater is that the transmissivities in the portions of the aquifer containing brackish water may be significantly lower than the favorable transmissivities reported above.

Availability- LOW to HIGH- Due to the large number of planning regions that the Yegua-Jackson aquifer crosses, availabilities by region vary widely, ranging from low to high. Availabilities are low in the down-dip portion of the aquifer. Most of the rest of the regions have average availabilities, with regions in Central Texas being considered moderate to high.

Productivity- LOW- Much of the brackish groundwater present in the Yegua-Jackson aquifer occurs at depth in the down-dip portion of this aquifer, where transmissivities are much lower than in the fresh water section. This results in a low productivity for the aquifer.

Source Water Production Cost- MODERATE to HIGH- Much of the brackish water present in this aquifer occurs at greater depths in the down-dip portions of the aquifer. Wells installed in these areas will be deeper and less productive, thus increasing the relative cost of producing from these areas. Only where brackish groundwater is found in and near the outcrop areas will relative costs be moderate.

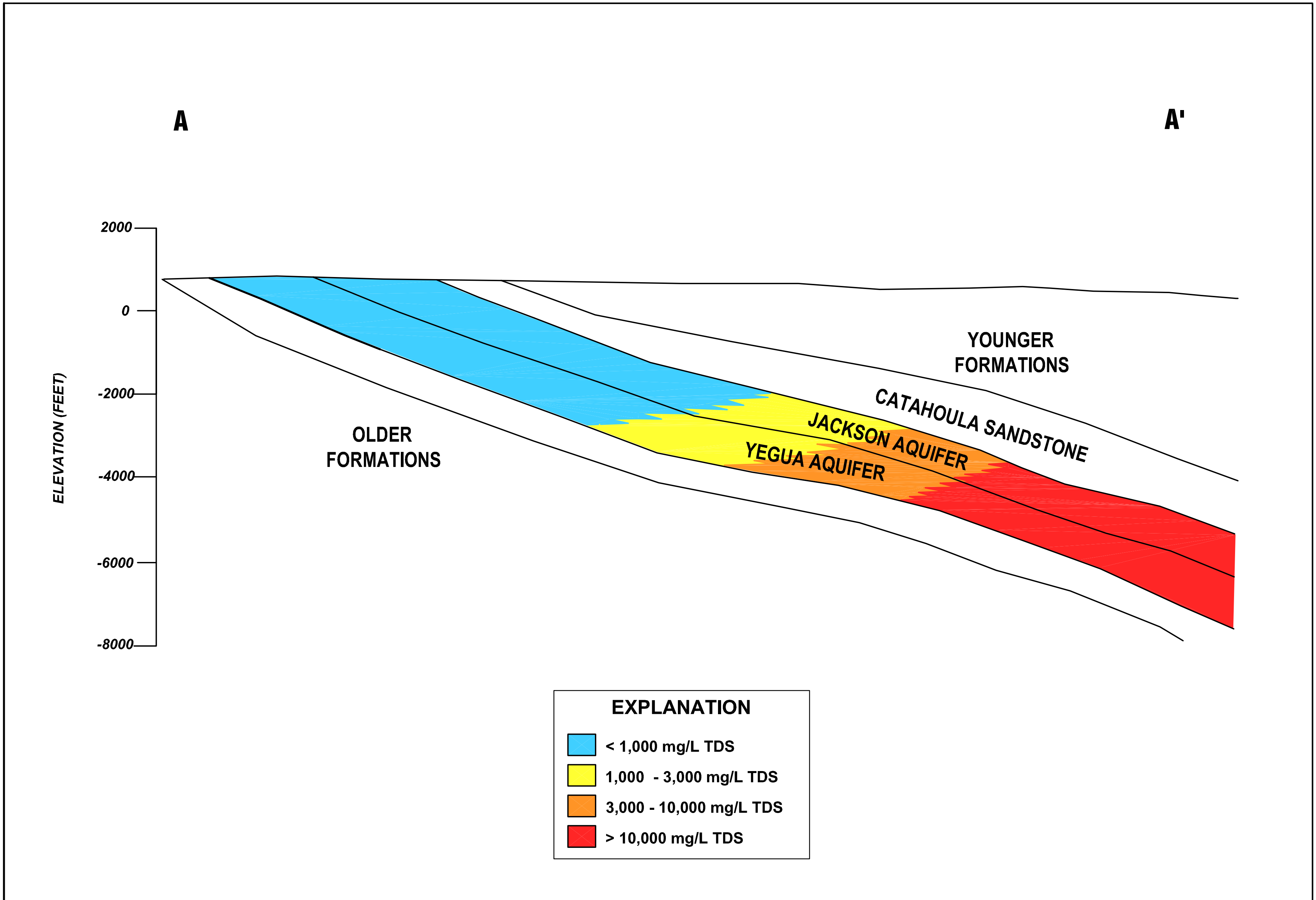
Summary of Brackish Water In the Yegua-Jackson Aquifer			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
G- Brazos	Moderate	Low	Moderate to High
H- Region H	Moderate	Low	Moderate
I- East Texas	Moderate	Low	Moderate
K- Lower Colorado	Moderate to High	Low	Moderate to High
L- South Central Texas	Moderate to High	Low	Moderate to High
M- Rio Grande	High	Low	Moderate
N- Coastal Bend	Low	Low	Moderate to High
P- Lavaca	Low	Low	High



GROUNDWATER QUALITY IN THE YEGUA-JACKSON AQUIFER

FIGURE 65

LBG-GUYTON ASSOCIATES



SIMPLIFIED CROSS SECTION OF THE YEGUA-JACKSON AQUIFER WITH GENERALIZED WATER QUALITY RANGES

(Modified from Baker, 1995)

FIGURE 66

LBG-GUYTON ASSOCIATES

3.2.21 River Alluviums

Shallow alluvial aquifers are formed in most of the floodplain deposits of major rivers present in the state. Although most of these shallow alluvial aquifers contain fresh water, there are several that contain some slightly- to moderately-saline water, including those formed by the Rio Grande, the upper Brazos River, and the upper Red River, as shown in Figure 67. Available data indicate the presence of higher TDS groundwater in other river alluvium aquifers in the state, including portions of the Colorado River. However, because these occurrences are limited and the majority of wells in these aquifers contain fresh water, these rivers are not included in this report.

Floodplain and terrace deposits consist of clay, silt, sand, and gravel, and can be up to 200 feet thick. The only shallow alluvial aquifer officially recognized as a minor aquifer by the TWDB is the Brazos River Alluvium aquifer. Although not an officially recognized aquifer, a significant amount of water is also present in the Rio Grande Alluvium aquifer, primarily in the El Paso area and the Lower Rio Grande Valley. Much of the water in the Rio Grande Alluvium aquifer has TDS concentrations greater than 1,000 mg/L.

Because of the high variability in the types of sediments in the shallow alluvial aquifers, wells completed in them may have variable productivity. The Rio Grande Alluvium may yield 1,000 to 2,000 gpm to wells, with maximum yields approaching 3,000 gpm. Yields of less than 500 gpm from the Rio Grande Alluvium are far less common than yields in excess of 1,000 gpm[1]. However, in the Brazos River Alluvium, most of the wells completed produce between 250 and 500 gpm, and more than one-quarter produce between 500 and 750 gpm[2].

The water quality in these shallow alluvial aquifers varies significantly. In many, the groundwater is dominated by fresh water. In others, including the ones described in this section, some wells may contain slightly- to moderately-saline water. In fact, in some areas, salinities of greater than 10,000 mg/L TDS can be found in alluvial groundwater. There do not appear to be any identifiable trends in salinity within the aquifers, nor is there generally any identifiable chemical type of groundwater present. Chemical quality of these groundwaters varies greatly, even over very short distances.

Summary

The most extensive sections of slightly- to moderately-saline water in an alluvial aquifer are present in the Rio Grande. Much or most of the Rio Grande Alluvium aquifer from El Paso to the Gulf of Mexico contain groundwater that has greater than 1,000 mg/L TDS. The Brazos River Alluvium aquifer also contains some brackish groundwater resources between Grimes and Hill Counties. In addition, water-quality data from the upper portions of the Red River Alluvium indicate some areas of slightly- to moderately-saline water.

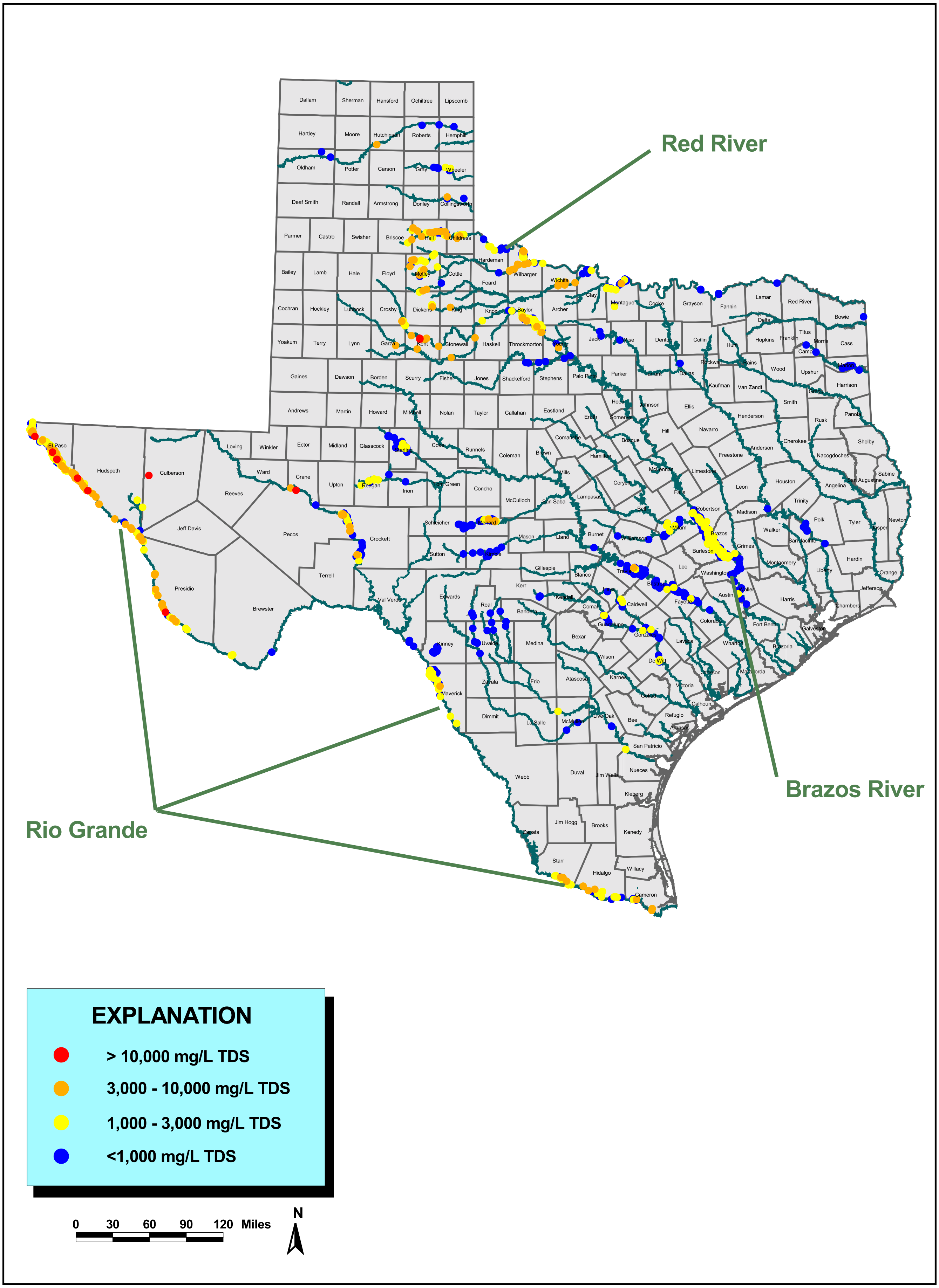
Some estimates of total water availability in shallow alluvial aquifers have previously been made. It is estimated that 2,760,000 acre-feet of mostly fresh water is present in the Brazos River Alluvium[2], and it has been estimated that the Rio Grande Alluvium aquifer in El Paso County has 1,400,000 acre-feet of water in storage with less than 2,500 mg/L[1].

Availability- MODERATE to HIGH- In river alluviums where brackish water occurs, the availability is moderate to high. Only in the Rio Grande and Brazos River Alluvium aquifers is brackish groundwater expected to be encountered on a consistent basis. In many of the other rivers, groundwater quality is highly variable throughout these river alluvium aquifers.

Productivity- HIGH- Where brackish groundwater is found, the productivity is high. River alluvium aquifers are usually fairly transmissive and very shallow.

Source Water Production Cost- LOW to MODERATE- Alluvial aquifer wells are shallow and relatively predictable as to productivity. In areas where high productivity can be expected out of the alluvial aquifer, production costs will be low. Where low to moderate productivity can be expected, production costs will be higher due to the increased number of wells that will be required.

Summary of Brackish Water In the River Alluvium Aquifers			
Region	*Availability*	*Productivity*	*Source Water Production Cost*
B- Region B	Moderate	High	Moderate
E- Far West Texas	High	High	Low to Moderate
F- Region F	Moderate	High	Moderate
G- Brazos	High	High	Low
M- Rio Grande	High	High	Moderate



GROUNDWATER QUALITY IN RIVER ALLUVIUM AQUIFERS

FIGURE 67

LBG-GUYTON ASSOCIATES

3.3 Brackish Groundwater Volumes by Aquifer and Region

The volume of brackish groundwater was estimated for each aquifer in each RWPA. These estimates were based on generalized aquifer characteristics in each region and are not intended to be used as precise availability values. They are included in this report to provide a means of evaluating whether a brackish groundwater desalination strategy is feasible in a RWPA and whether or not it should be evaluated further. Please see Chapter 2 for a discussion of the limitations and assumptions in the model.

Table 5 summarizes the estimated volume of brackish groundwater in each aquifer and RWPA. In addition, the total brackish groundwater volumes for each aquifer are shown in Table 5. Table 5 is grouped by major and minor aquifers and arranged in alphabetical order within each group. Also shown in the table are the aquifer parameters used to estimate the brackish groundwater volumes including:

- *Estimated average specific yield* - used to estimate total volume of unconfined brackish groundwater available
- *Estimated storativity* – used to estimate the minimum volume of brackish groundwater currently in confined storage in the aquifer
- *Approximate areal extent 1,000 to 3,000 and 3,000 to 10,000 TDS water* – used in volume calculations
- *Estimated average thickness of productive units* – The average total thickness of aquifer material containing brackish groundwater that can be produced by wells, which was used in volume
- *Assumed aquifer drawdown* – For confined aquifer sections, the volume of reasonably retrievable brackish groundwater in storage was estimated by assuming the water levels would decline a specified amount during development
- *Estimated volume of brackish groundwater "in place"* – Estimate of the total amount of brackish groundwater currently in unconfined storage in the aquifer. If the aquifer is unconfined, the volume of brackish groundwater currently in place is an estimate of the total availability if the aquifer were completely dewatered.
- *Estimated confined availability* - If the aquifer or aquifer section is confined, the volume of brackish groundwater currently in place that could be developed if the water levels were decreased by the assumed aquifer drawdown

Table 5. Estimated Volume of Brackish Groundwater in Each Aquifer

Aquifer	Region	Estimated Average Specific Yield	Estimated Storativity	Approximate Areal Extent 1000-3000 TDS (sq. mi)	Approximate Areal Extent 3000-10000 TDS (sq. mi)	Estimated Average Thickness of Productive Units (feet)	Assumed Aquifer Drawdown (feet)	Estimated Volume "In Place" (acre-feet)	Estimated Confined Availablility (acre-feet)
Major Aquifers									
Carrizo-Wilcox	C- Region C	--	--	0	0	--	--	--	--
Carrizo-Wilcox	D- Northeast Texas	--	--	0	0	--	--	--	--
Carrizo-Wilcox	G- Brazos	0.15	5E-04	550	400	625	300	57,000,000	91,200
Carrizo-Wilcox	H- Region H	0.15	5E-04	260	220	500	300	23,040,000	46,100
Carrizo-Wilcox	I- East Texas	0.15	5E-04	1220	540	500	200	84,480,000	112,600
Carrizo-Wilcox	K- Lower Colorado	0.15	5E-04	230	340	625	300	34,200,000	54,700
Carrizo-Wilcox	L- South Central Texas	0.15	5E-04	950	370	1000	300	126,720,000	126,700
Carrizo-Wilcox	M- Rio Grande	0.10	5E-04	1010	680	250	200	27,040,000	108,200
Carrizo-Wilcox	N- Coastal Bend	0.10	5E-04	675	425	1000	400	70,400,000	140,800
Carrizo-Wilcox	P- Lavaca	0.10	5E-04	30	135	625	400	6,600,000	21,100
Carrizo-Wilcox-Total								**429,480,000**	**701,400**
Cenozoic Pecos Alluvium	F- Region F	0.12	--	4950	110	300	--	116,582,400	--
Cenozoic Pecos Alluvium-Total								**116,582,400**	--
Edwards-BFZ	G- Brazos	0.05	1E-04	200	140	400	500	4,352,000	10,900
Edwards-BFZ	J- Plateau	0.05	1E-04	160	275	500	500	6,960,000	13,900
Edwards-BFZ	K- Lower Colorado	0.05	1E-04	90	100	400	500	2,432,000	6,100
Edwards-BFZ	L- South Central Texas	0.05	1E-04	500	1070	500	500	25,120,000	50,200
Edwards-BFZ-Total								**38,864,000**	**81,100**
Edwards-Trinity (Plateau)	E- Far West Texas	--	--	0	0	--	--	--	--
Edwards-Trinity (Plateau)	F- Region F	0.08	1E-04	2900	255	150	150	24,230,400	30,300
Edwards-Trinity (Plateau)	G- Brazos	--	--	0	0	--	--	--	--
Edwards-Trinity (Plateau)	J- Plateau	--	--	0	0	--	--	--	--
Edwards-Trinity (Plateau)	K- Lower Colorado	--	--	0	0	--	--	--	--
Edwards-Trinity (Plateau)	L- South Central Texas	--	--	0	0	--	--	--	--
Edwards-Trinity (Plateau)-Total								**24,230,400**	**30,300**
Gulf Coast	G- Brazos	--	--	0	0	--	--	--	--
Gulf Coast	H- Region H	0.15	7E-04	1580	650	400	200	85,632,000	199,800
Gulf Coast	I- East Texas	0.15	7E-04	680	350	400	300	39,552,000	138,400
Gulf Coast	K- Lower Colorado	0.15	7E-04	400	710	300	300	31,968,000	149,200
Gulf Coast	L- South Central Texas	0.15	7E-04	1200	400	300	300	46,080,000	215,000
Gulf Coast	M- Rio Grande	0.15	7E-04	4360	1380	250	200	137,760,000	514,300
Gulf Coast	N- Coastal Bend	0.15	7E-04	4810	2660	250	300	179,280,000	1,004,000
Gulf Coast	P- Lavaca	--	--	0	0	--	--	--	--
Gulf Coast-Total								**520,272,000**	**2,220,700**
Hueco Bolson	E- Far West Texas	0.15	1E-04	850	0	300	200	24,480,000	10,900
Hueco Bolson-Total								**24,480,000**	**10,900**
Mesilla Bolson	E- Far West Texas	0.15	1E-04	10	0	500	200	480,000	100
Mesilla Bolson-Total								**480,000**	**100**
Ogallala	A- Panhandle	--	--	0	0	--	--	--	--
Ogallala	F- Region F	0.15	--	1235	360	50	50	7,656,000	--
Ogallala	O- Llano Estacado	0.15	--	3490	230	80	80	28,569,600	--
Ogallala-Total								**36,225,600**	--
Seymour	A- Panhandle	0.15	--	20	0	50	50	96,000	--
Seymour	B- Region B	0.15	--	40	0	50	50	192,000	--
Seymour	G- Brazos	0.15	--	415	0	50	50	1,992,000	--
Seymour	O- Llano Estacado	--	--	0	0	--	--	--	--
Seymour-Total								**2,280,000**	
Trinity	B- Region B	--	--	0	0	--	--	--	--
Trinity	C- Region C	0.10	2E-04	945	910	500	200	59,360,000	47,500
Trinity	D- Region D	0.05	2E-04	790	630	600	200	27,264,000	36,400
Trinity	F- Region F	--	--	0	0	--	--	--	--
Trinity	G- Brazos	0.10	2E-04	2200	1600	300	200	72,960,000	97,300
Trinity	J- Plateau	--	--	0	0	--	--	--	--
Trinity	K- Lower Colorado	0.03	2E-04	500	450	200	200	3,648,000	24,300
Trinity	L- South Central Texas	0.03	2E-04	2010	1800	200	200	14,630,400	97,500
Trinity-Total								**177,862,400**	**303,000**
Minor Aquifers									
Blaine	A- Panhandle	0.02	--	375	730	500	200	7,072,000	--
Blaine	B- Region B	0.02	--	900	900	500	200	11,520,000	--
Blaine	F- Region F	--	--	0	0	--	--	--	--
Blaine	G- Brazos	0.02	--	200	200	200	200	1,024,000	--
Blaine-Total								**19,616,000**	

Table 5. Estimated Volume of Brackish Groundwater in Each Aquifer

Aquifer	Region	Estimated Average Specific Yield	Estimated Storativity	Approximate Areal Extent 1000-3000 TDS (sq. mi)	Approximate Areal Extent 3000-10000 TDS (sq. mi)	Estimated Average Thickness of Productive Units (feet)	Assumed Aquifer Drawdown (feet)	Estimated Volume "In Place" (acre-feet)	Estimated Confined Availablility (acre-feet)
Blossom	D- North East Texas	0.10	5E-05	170	50	100	100	1,408,000	700
Blossom-Total								**1,408,000**	**700**
Bone Spring-Victorio Peak	E- Far West Texas	0.05	--	100	40	2000	--	8,960,000	--
Bone Spring-Victorio Peak-Total								**8,960,000**	**--**
Capitan Reef	E- Far West Texas	0.05	1E-03	550	0	1500	800	26,400,000	281,600
Capitan Reef	F- Region F	0.05	1E-03	570	420	1500	800	47,520,000	506,900
Capitan Reef-Total								**73,920,000**	**788,500**
Dockum	A- Panhandle	0.05	1E-04	700	0	200	200	4,480,000	9,000
Dockum	F- Region F	0.05	1E-04	8500	5065	150	150	65,112,000	130,200
Dockum	O- Llano Estacado	0.05	1E-04	1760	5130	250	200	55,120,000	88,200
Dockum-Total								**124,712,000**	**227,400**
Edwards-Trinity (High Plains)	O- Llano Estacado	0.01	1E-04	5930	135	150	150	5,822,400	58,200
Edwards-Trinity (High Plains)-Total								**5,822,400**	**58,200**
Ellenburger-San Saba	F- Region F	0.03	2E-03	900	1460	500	200	22,656,000	604,200
Ellenburger-San Saba	G- Brazos	0.03	2E-03	190	430	100	100	1,190,400	79,400
Ellenburger-San Saba	J- Plateau	0.03	2E-03	310	500	100	100	1,555,200	103,700
Ellenburger-San Saba	K- Lower Colorado	0.03	2E-03	810	1160	500	200	18,912,000	504,300
Ellenburger-San Saba	L- South Central Texas	0.03	2E-03	120	310	100	100	825,600	55,000
Ellenburger-San Saba-Total								**45,139,200**	**1,346,600**
Hickory	F- Region F	0.15	1E-04	600	475	500	200	51,600,000	13,800
Hickory	G- Brazos	0.15	1E-04	100	230	Unknown	200	Unknown	4,200
Hickory	J- Plateau	0.15	1E-04	110	280	Unknown	200	Unknown	5,000
Hickory	K- Lower Colorado	0.15	1E-04	835	550	500	200	66,480,000	17,700
Hickory	L- South Central Texas	0.15	1E-04	150	135	Unknown	200	Unknown	3,600
Hickory-Total								**118,080,000**	**44,300**
Igneous	E- Far West Texas	--	--	0	0	--	--	--	--
Igneous-Total								**0**	**0**
Lipan	F- Region F	0.05	1E-04	500	20	75	75	1,248,000	2,500
Lipan-Total								**1,248,000**	**2,500**
Marathon	E- Far West Texas	--	--	0	0	--	--	--	--
Marathon-Total								**0**	**0**
Marble Falls	F- Region F	--	--	0	0	--	--	--	--
Marble Falls	G- Brazos	--	--	0	0	--	--	--	--
Marble Falls	J- Plateau	--	--	0	0	--	--	--	--
Marble Falls	K- Lower Colorado	--	--	0	0	--	--	--	--
Marble Falls	L- South Central Texas	--	--	0	0	--	--	--	--
Marble Falls-Total								**0**	**0**
Nacatoch	C- Region C	0.10	1E-04	390	140	50	50	1,696,000	1,700
Nacatoch	D- North East Texas	0.10	1E-04	750	230	200	200	12,544,000	12,500
Nacatoch-Total								**14,240,000**	**14,200**
Queen City-Sparta	C- Region C	--	--	0	0	--	--	--	--
Queen City-Sparta	D- North East Texas	--	--	0	0	--	--	--	--
Queen City-Sparta	G- Brazos	0.15	5E-04	850	210	250	200	25,440,000	67,800
Queen City-Sparta	H- Region H	0.15	5E-04	360	220	250	200	13,920,000	37,100
Queen City-Sparta	I- East Texas	0.15	5E-04	760	490	75	50	9,000,000	20,000
Queen City-Sparta	K- Lower Colorado	0.15	5E-04	610	160	250	200	18,480,000	49,300
Queen City-Sparta	L- South Central Texas	0.10	5E-04	4200	550	250	200	76,000,000	304,000
Queen City-Sparta	M- Rio Grande	0.10	5E-04	1700	1830	400	200	90,368,000	225,900
Queen City-Sparta	N- Coastal Bend	0.10	5E-04	350	200	300	200	10560000	35,200
Queen City-Sparta	P- Lavaca	0.10	5E-04	10	65	250	200	1200000	4,800
Queen City-Sparta-Total								**244,968,000**	**744,100**
Rita Blanca	A- Panhandle	--	--	0	0	--	--	--	--
Rita Blanca-Total								**0**	**0**
Rustler	E- Far West Texas	0.03	2E-05	330	330	150	150	1,900,800	1,300
Rustler	F- Region F	0.03	2E-05	2275	2275	400	200	34,944,000	11,600
Rustler-Total								**36,844,800**	**12,900**
West Texas Bolsons	E- Far West Texas	0.15	6E-04	1090	0	600	200	62,784,000	83,700
West Texas Bolsons-Total								**62,784,000**	**83,700**

Table 5. Estimated Volume of Brackish Groundwater in Each Aquifer

Aquifer	Region	Estimated Average Specific Yield	Estimated Storativity	Approximate Areal Extent 1000-3000 TDS (sq. mi)	Approximate Areal Extent 3000-10000 TDS (sq. mi)	Estimated Average Thickness of Productive Units (feet)	Assumed Aquifer Drawdown (feet)	Estimated Volume "In Place" (acre-feet)	Estimated Confined Availablility (acre-feet)
Whitehorse-Artesia	A- Panhandle	0.02	1E-04	175	1275	400	200	7,424,000	18,600
Whitehorse-Artesia	B- Region B	0.02	1E-04	0	550	400	200	2,816,000	7,000
Whitehorse-Artesia	F- Region F	--	--	0	0	--	--	--	--
Whitehorse-Artesia	G- Brazos	0.02	1E-04	0	910	400	200	4,659,200	11,600
Whitehorse-Artesia	O- Llano Estacado	0.02	1E-04	0	410	400	200	2,099,200	5,200
Whitehorse-Artesia-Total								**14,899,200**	**37,200**
Woodbine	C- Region C	0.10	2E-04	1850	1870	100	100	23,808,000	35,700
Woodbine	D- North East Texas	0.10	2E-04	310	1200	150	150	14,496,000	21,700
Woodbine	G- Brazos	0.10	2E-04	380	460	100	100	5,376,000	8,100
Woodbine-Total								**43,680,000**	**65,500**
Yegua-Jackson	G- Brazos	0.15	1E-03	380	60	500	200	21,120,000	56,300
Yegua-Jackson	H- Region H	0.15	1E-03	670	795	500	200	70,320,000	187,500
Yegua-Jackson	I- East Texas	0.15	1E-03	670	630	500	200	62,400,000	166,400
Yegua-Jackson	K- Lower Colorado	0.15	1E-03	220	300	500	200	24,960,000	66,600
Yegua-Jackson	L- South Central Texas	0.15	1E-03	1900	750	500	200	127,200,000	339,200
Yegua-Jackson	M- Rio Grande	0.15	1E-03	2200	710	500	200	139,680,000	372,500
Yegua-Jackson	N- Coastal Bend	0.15	1E-03	710	765	500	200	70,800,000	188,800
Yegua-Jackson	P- Lavaca	--	--	0	0	--	--	--	--
Yegua-Jackson-Total								**337,680,000**	**900,500**

Table 6 shows the estimated total brackish groundwater volumes in each RWPA. Section 2.4.5 describes the assumptions and methods used to estimate these volumes. The total minimum confined volume of brackish groundwater in all Texas aquifers is approximately 8 million acre-feet. The estimated total available fresh groundwater for all the major and minor aquifers in Texas in 2000 was 14,900,000 acre-feet/year (TWDB, 2002). Therefore, brackish groundwater represents a significant resource for the State of Texas. The total estimated volume of brackish groundwater "in place" in Texas aquifers is over 2.5 billion acre-feet.

Table 6. Estimated Brackish Groundwater Volume by Region

Region	Total Estimated Volume of Brackish Groundwater "In Place" in all Aquifers (acre/feet)	Total Minimum Confined Volume of Brackish Groundwater (acre/feet)
A- Panhandle	19,072,000	27,600
B- Region B	14,528,000	7,000
C- Region C	84,864,000	84,900
D- Northeast Texas	55,712,000	71,300
E- Far West Texas	125,004,800	377,600
F- Region F	371,548,800	1,299,500
G- Brazos	195,113,600	426,800
H- Region H	192,912,000	470,500
I- East Texas	195,432,000	437,400
J- Plateau	8,515,200	122,600
K- Lower Colorado	201,080,000	872,200
L- South Central Texas	416,576,000	1,191,200
M- Rio Grande	394,848,000	1,220,900
N- Coastal Bend	331,040,000	1,368,800
O- Llano Estacado	91,611,200	151,600
P- Lavaca	7,800,000	25,900
Total	**2,705,657,600**	**8,155,800**

4.0 COST ANALYSIS OF GROUNDWATER DESALINATION

Providing data related to the cost of water, both to policy-makers and water utilities providers, in a timely and accurate manner is critical to ensuring future water supplies in Texas. The evaluation of water management strategies for the regional water planning process requires cost estimates for each proposed strategy. This section provides basic formulas to help estimate the costs of proposed brackish groundwater desalination projects.

4.1 Summary of Previous Work Completed by TWDB and Other Entities

Realizing that Texas would require innovative water-supply alternatives, the TWDB commissioned a study of desalination for water supply that was completed in August 2000. The report (HDR and others, 2000) provides an excellent overview of desalination technologies, including reverse osmosis (RO) and electrodialysis reversal (EDR). The report summarizes the process selection for desalination, including water quality, treatment objectives, and costs. Cost components evaluated in the report include pretreatment, feedwater pumping, cartridge filtration, disinfection, membrane filtration, membrane cleaning, and concentrate disposal. The cost of reverse osmosis systems for groundwater desalination can be estimated using the methodology in the report. The following sections contain a summary of the report pertaining to brackish groundwater desalination costs.

In addition, work completed by NRS Consulting Engineers (NRS) has been used to supplement the engineering cost data included in the HDR and others (2000) report. NRS has completed extensive engineering and cost estimation work in the Rio Grande Valley of Texas regarding planning and implementation of brackish groundwater desalination systems since the HDR report was published. Therefore, the findings from this work have been summarized in this report as well.

4.2 Cost Analysis for Treatment of Brackish Groundwater

HDR and others (2000) present detailed information about construction and operation and maintenance (O&M) costs for brackish groundwater desalination facilities. The cost estimation method is suitable for detailed planning purposes and is illustrated by an example of a cost estimate provided in the HDR report. For completeness, some of the graphics from the HDR report concerning capital, O&M, and total treatment costs have been included in this document. However, it is recommended that the reader refer to the original report for a more complete discussion of the assumptions incorporated in the analysis. The following section discusses the total cost to treat brackish groundwater and subsequent sections discuss individual components of the total cost, including capital, O&M, energy, and pretreatment costs.

4.2.1 Total Costs of Treated Brackish Groundwater

The data for the cost estimates presented by HDR and others (2000) were developed by a survey of operating groundwater desalination plants. Although the data for the plots are somewhat limited due to the limited number of operating plants, the results of the survey are useful for estimating costs associated with proposed brackish groundwater desalination strategies associated with regional water planning. It should also be noted that 11 groundwater desalination plants responded to the survey. Ten of the 11 plants surveyed used reverse osmosis technology and one used electrodialysis reversal. Cost estimates (capital and O&M)) were presented in year 2000 dollars. Capital costs for older plants were adjusted to year 2000 values using standard cost indices. Prior to using the following data to estimate costs, all the assumptions incorporated in the HDR analysis should be reviewed, and if necessary appropriate adjustments made for project specific conditions.

Figure 68 (after HDR and others, 2000) illustrates the total treated water costs for brackish groundwater desalination for plant capacities up to 15 million gallons per day (MGD). The total treated water costs are the sum of the amortized capital costs and the O&M costs. Capital was amortized over 20 years at 8% interest. This relationship was developed without consideration of TDS concentration in the brackish groundwater. Figure 68 clearly shows an economy of scale in the total treatment cost. The total treated water costs range from $1.50/Kgal to $2.75/Kgal. Thus, a simple formula for estimating total treatment cost (TTC) based on plant capacity (up to 15 MGD) is shown in Equation 1 below.

$$TTC = -0.071C + 2.43 \qquad \text{(Equation 1)}$$

where:

TTC = total treatment cost ($/Kgal)
C = plant capacity (MGD)

HDR and others (2000) conclude that for the systems analyzed, operation and maintenance costs associated with reverse osmosis treatment show considerable economy of scale. In addition, it concludes that concentrate disposal costs are very site specific and should be estimated using standard engineering approaches. The estimates do not include costs for source water development. A simplified method to estimate the costs associated with brackish groundwater development (i.e., wells and well fields for producing brackish groundwater) and disposal are estimated and summarized later in this chapter.

Because of current technology advances, the above formula should be used only as a guideline, as recent data and projections indicate lower costs than those published in the HDR and others (2000) report. Evaluation factors for comparison should include current and future regulation related to water quality and the cost and availability of other raw water resources. Site-specific conditions can greatly increase or reduce projected costs.

4.2.2 Capital Costs

Figure 69 (after HDR and others, 2000) illustrates the estimated capital costs associated with brackish groundwater desalination. Figure 69 indicates that capital costs can vary significantly from $2/gpd to $4/gpd and may exhibit slight economies of scale. The report indicates that the high variability in the capital costs may be a function of the

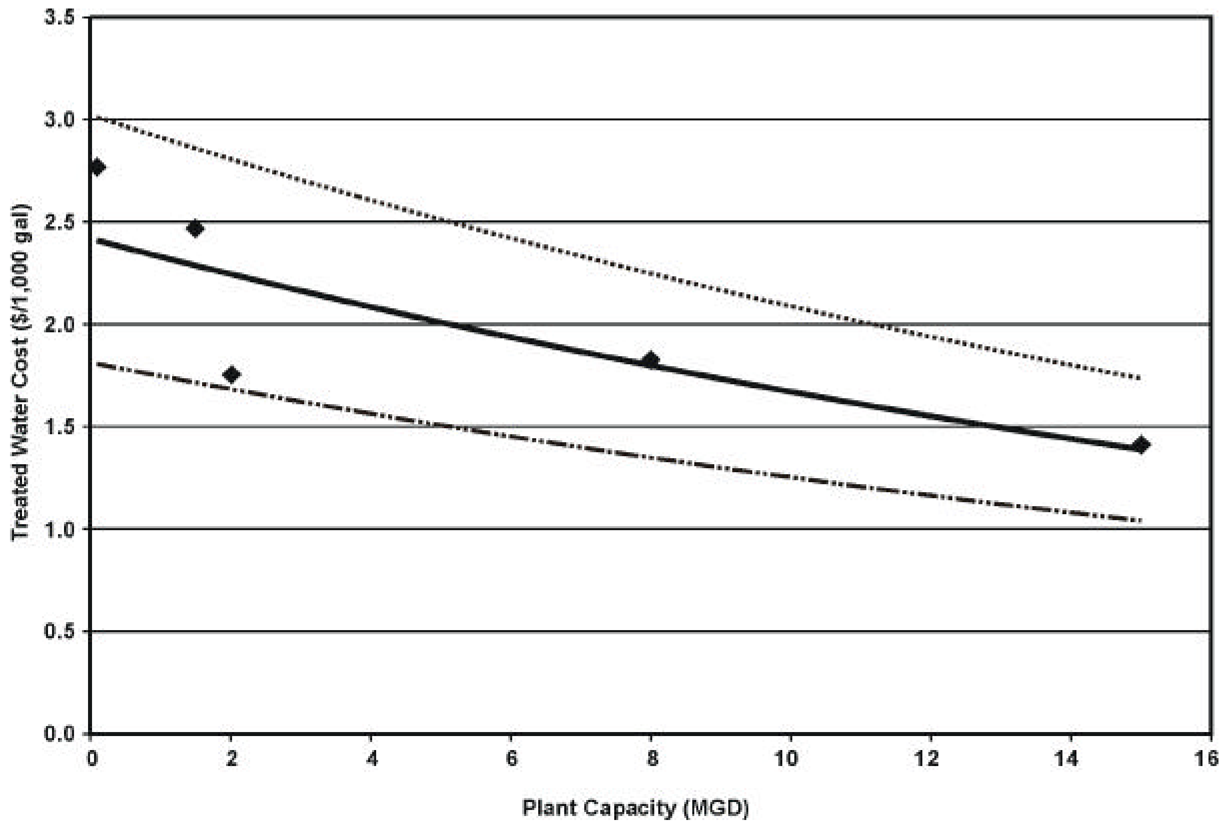


Figure 68. Total Treatment Cost for Brackish Groundwater Desalination (after HDR and others, 2000)

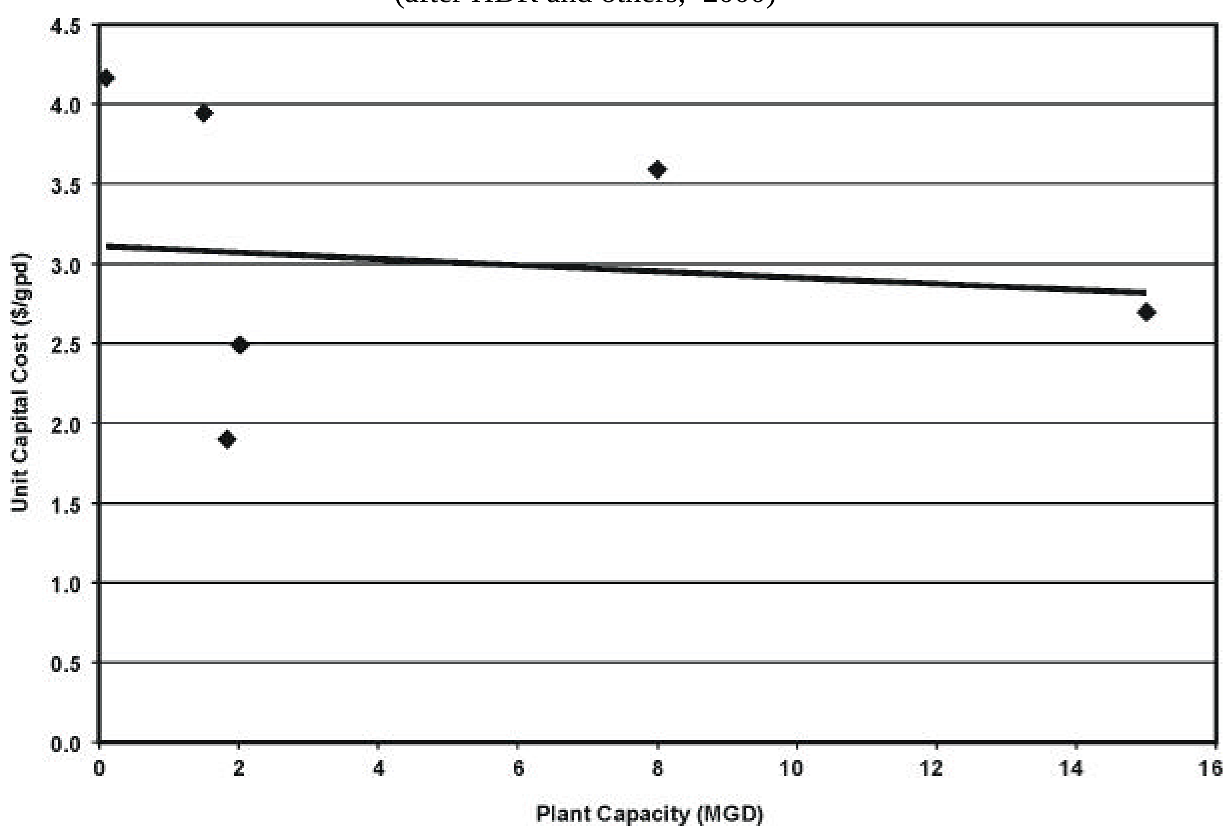


Figure 69. Capital Costs Associated with Brackish Groundwater Desalination (after HDR and others, 2000)

"coarse" nature of the survey. Capital costs include cost of initial construction and expansions, which were summed and divided by the resulting plant capacity to yield the unit cost for plant construction.

Figure 70 illustrates more recent data compiled by NRS Consulting Engineers regarding capital costs for a facility treating 3,000 mg/L TDS groundwater, including building and equipment, but do not include the source water and the treated water distribution and pumping system. The data were compiled through actual and projected treatment costs for recent projects. These costs are greatly dependent upon key factors including site specific conditions, degree of total dissolved solids, pretreatment requirement, capacity of the system, and over-sizing for future needs. Economies of scale play a significant role in the development of these facilities. Regional projects can provide for an overall reduction in costs for the end user, as do technology advances. Because of the rapid changes in treatment technology, data that is over two or three years old may be higher than current costs.

4.2.3 Operation and Maintenance Costs

Figure 71 (after HDR and others, 2000) illustrates the estimated O&M costs associated with brackish groundwater desalination. Figure 71 indicates that the O&M costs exhibit economies of scale and ranged from $0.60 to $1.60. This estimate of operation and maintenance costs includes the cost of personnel, chemicals, power, membrane/parts replacement, concentrate disposal and other costs. The report indicates that variations in O&M costs may reflect source-water quality such as TDS concentration.

4.2.4 Energy Costs

One of the most significant cost factors for brackish groundwater desalination is the cost of energy to force brackish groundwater through the membranes. A 3,000 mg/L TDS may be treated at less than 200 pounds per square inch (psi) while seawater at 30,000 mg/L TDS could require in excess of 1,000 psi pumping pressures. The lower the salt content the lower the pressure requirement. Technological advances in membranes make it possible for TDS to be removed at much lower pressures than just a few years ago. Figure 72 shows recent data compiled by NRS Consulting Engineers indicating the effect of variable power costs on the total energy costs required to treat 3,000 mg/L TDS source water. Recent advances in energy recovery of these systems can lower the power cost of the facility. In addition, energy deregulation allows for shopping of power for lower costs.

As a general rule, the higher the salt content of the brackish groundwater, the higher the pressure required for feed pumping. Compared to desalination of seawater, pressure requirements for brackish groundwater (i.e., less than 10000 mg/L TDS) are significantly reduced. As shown in Figure 73, construction cost for feed pumping increase for increased pressure requirements. O&M costs for RO feed pumping increase significantly for increased pressure requirements. Figures 74 through 76 indicate the O&M costs for various production levels under low (300 psi), medium (500 psi), and

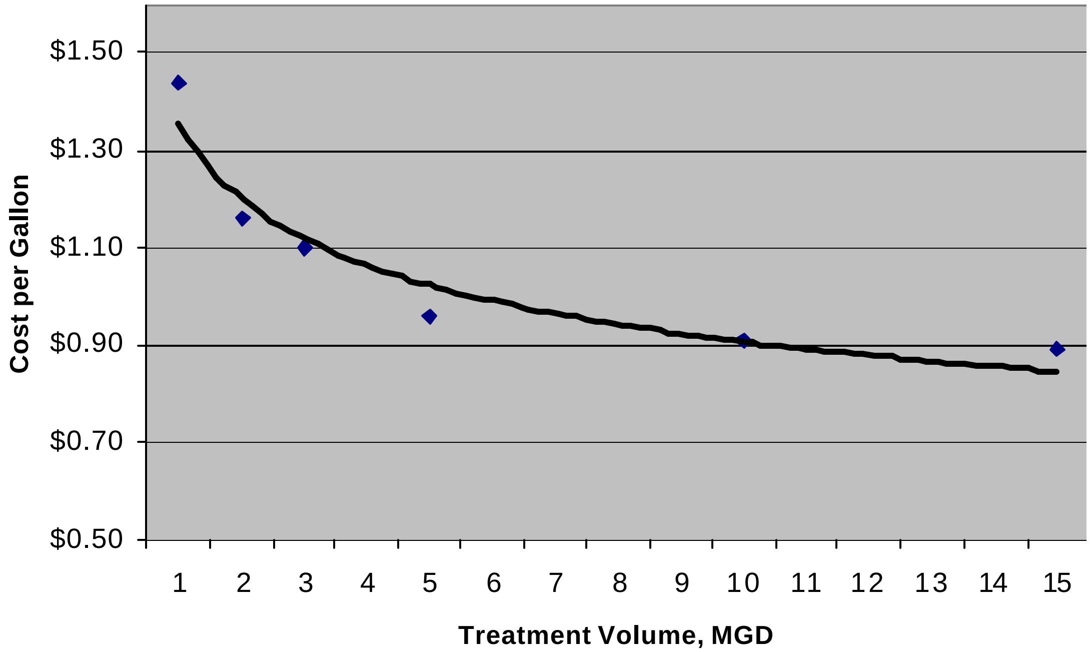


Figure 70. Recent Capital Costs for a Facility Treating 3000 mg/L Brackish Groundwater (Data Compiled by NRS Consulting Engineers)

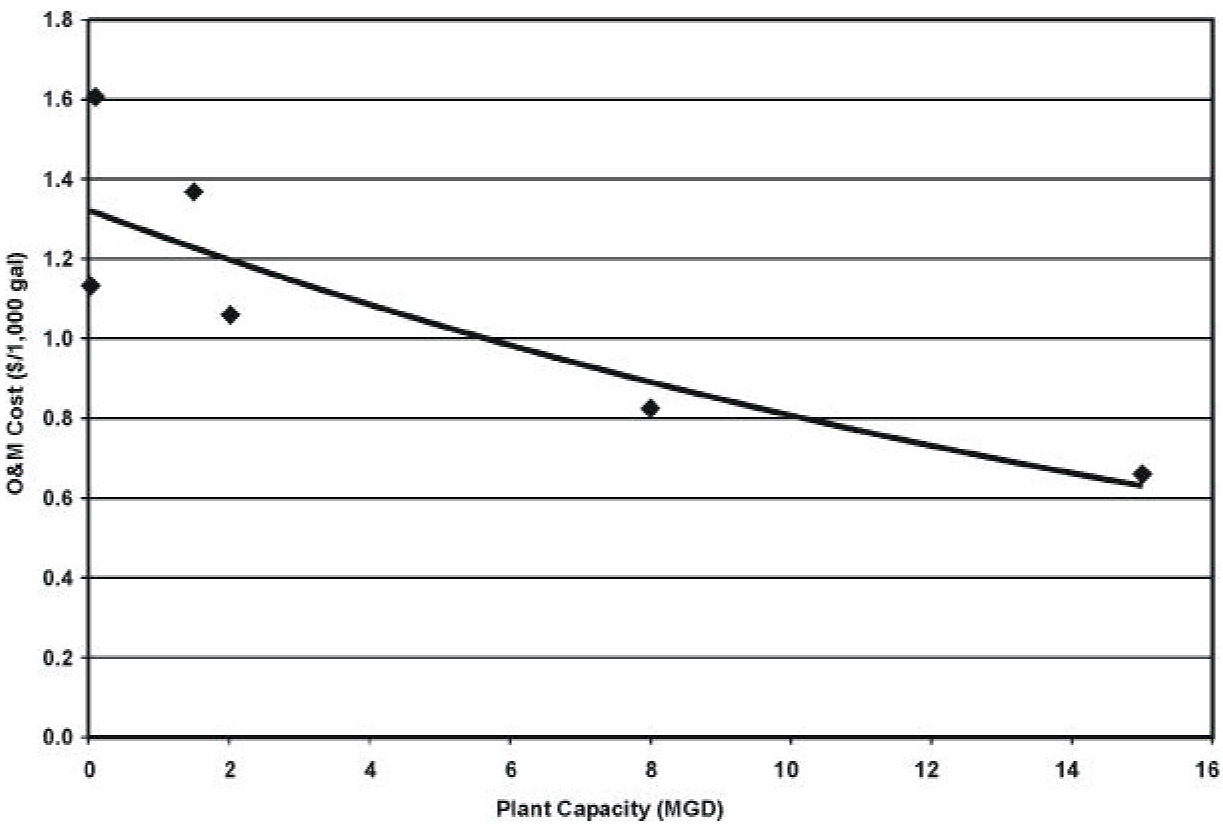


Figure 71. O&M Costs for Brackish Groundwater Desalination (after HDR and others, 2000)

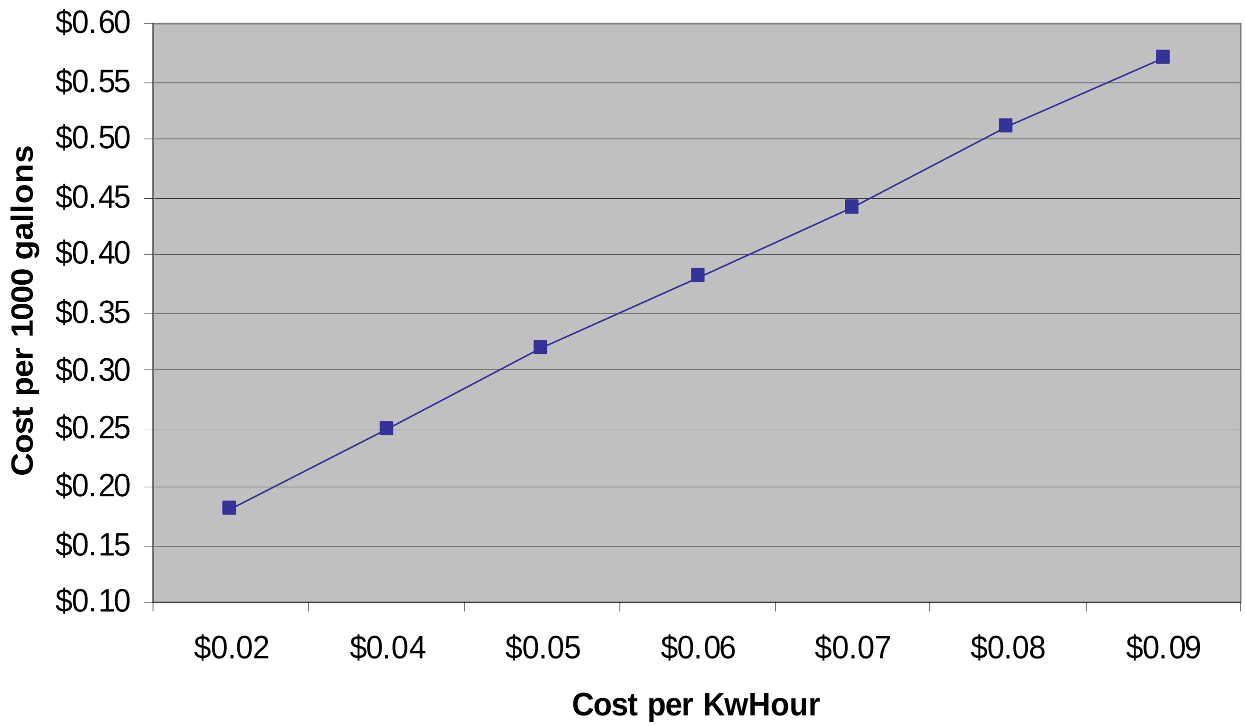
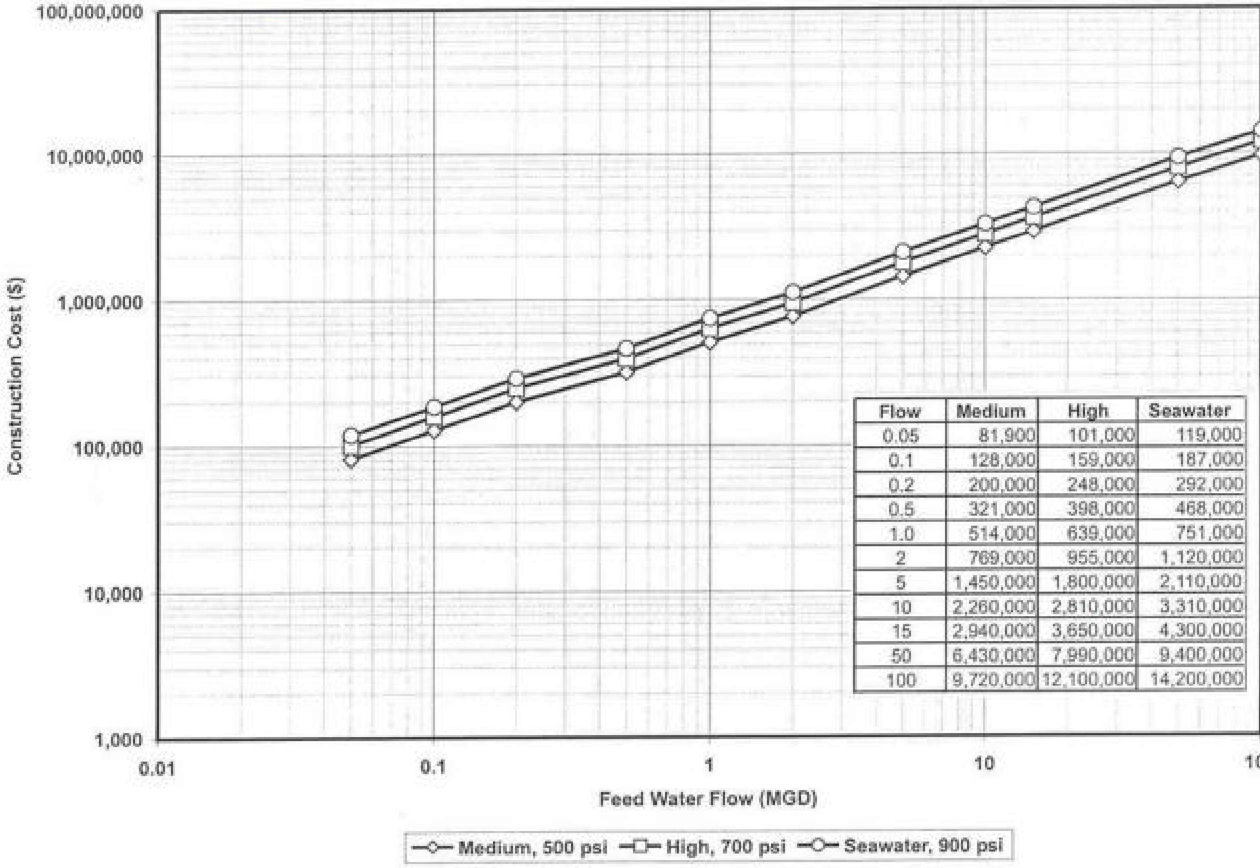
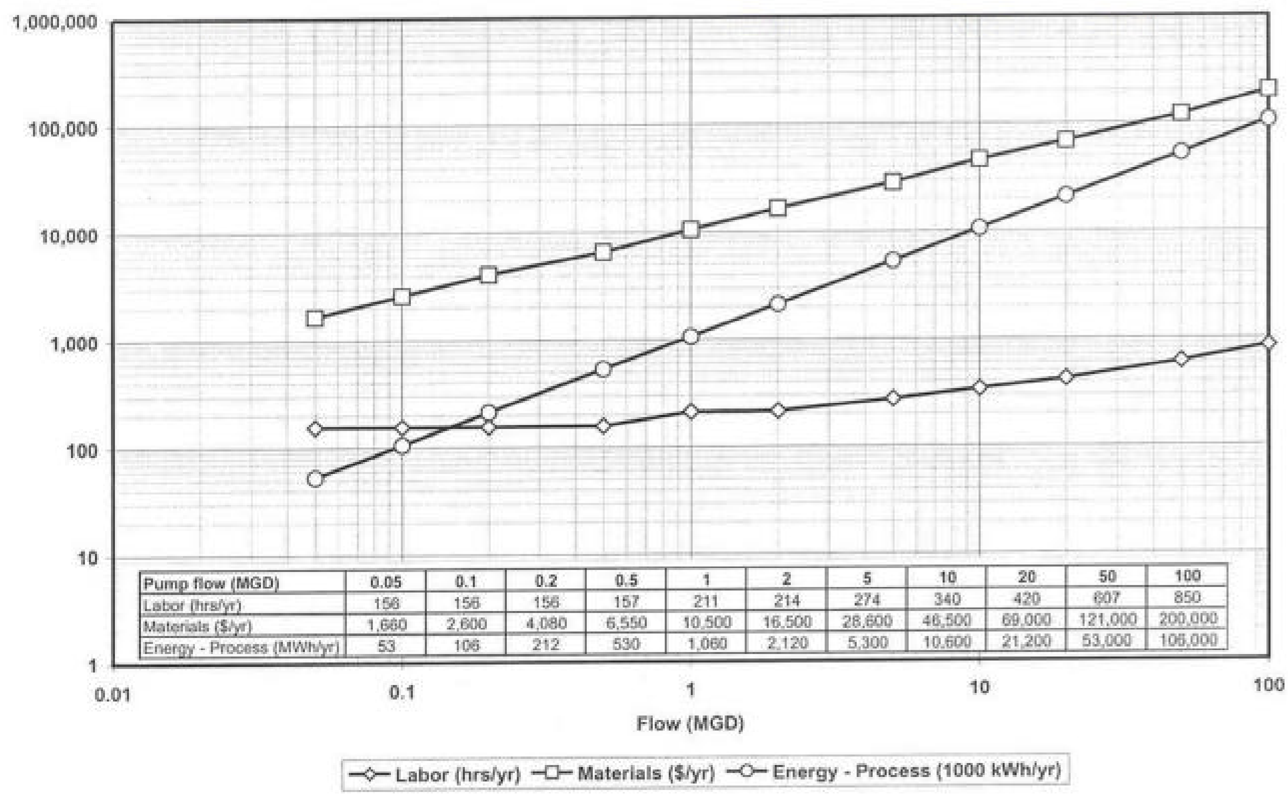


Figure 72. Recent Data Indicating the Effect of Power Costs for Treating 3000 mg/L Brackish Groundwater
(Data Compiled by NRS Consulting Engineers)



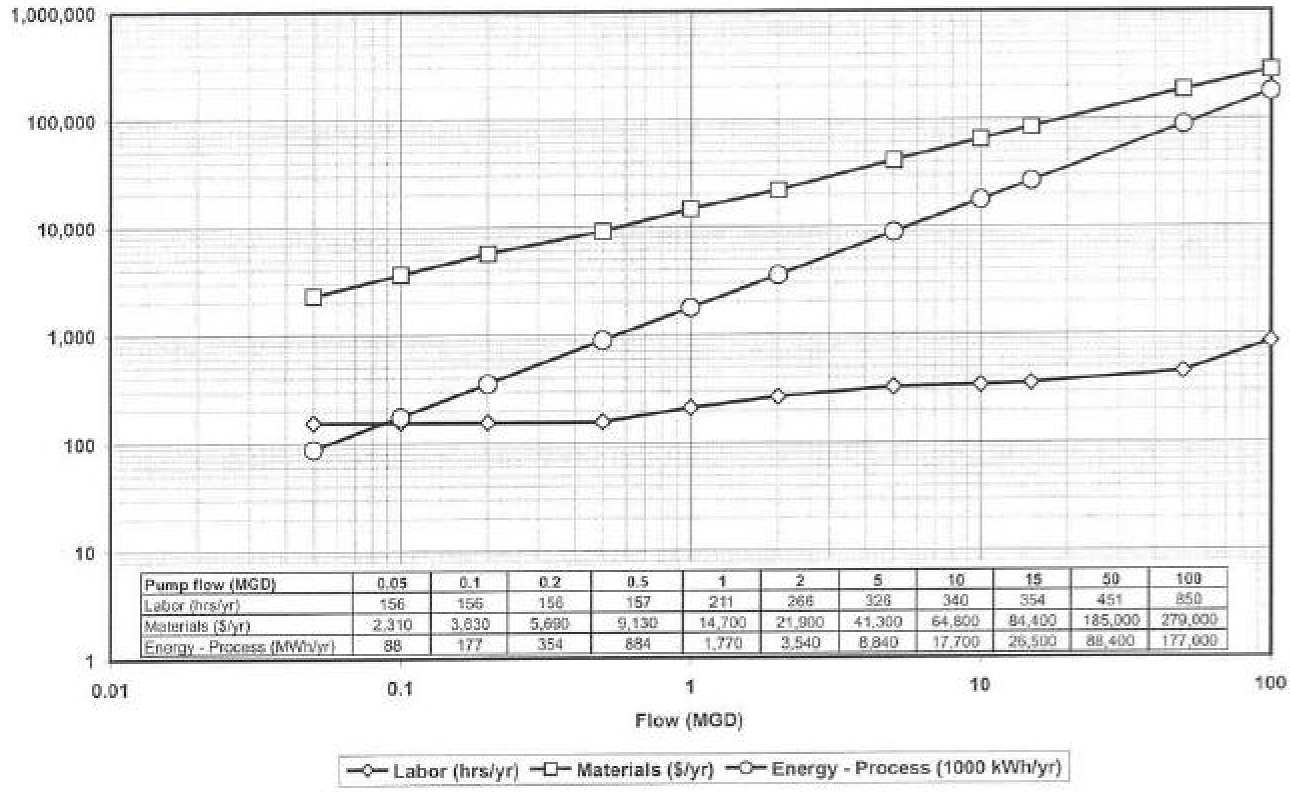
Flow	Medium	High	Seawater
0.05	81,900	101,000	119,000
0.1	128,000	159,000	187,000
0.2	200,000	248,000	292,000
0.5	321,000	398,000	468,000
1.0	514,000	639,000	751,000
2	769,000	955,000	1,120,000
5	1,450,000	1,800,000	2,110,000
10	2,260,000	2,810,000	3,310,000
15	2,940,000	3,650,000	4,300,000
50	6,430,000	7,990,000	9,400,000
100	9,720,000	12,100,000	14,200,000

Figure 73. O&M Costs for Reverse Osmosis Feed Pumping (after HDR and others, 2000)



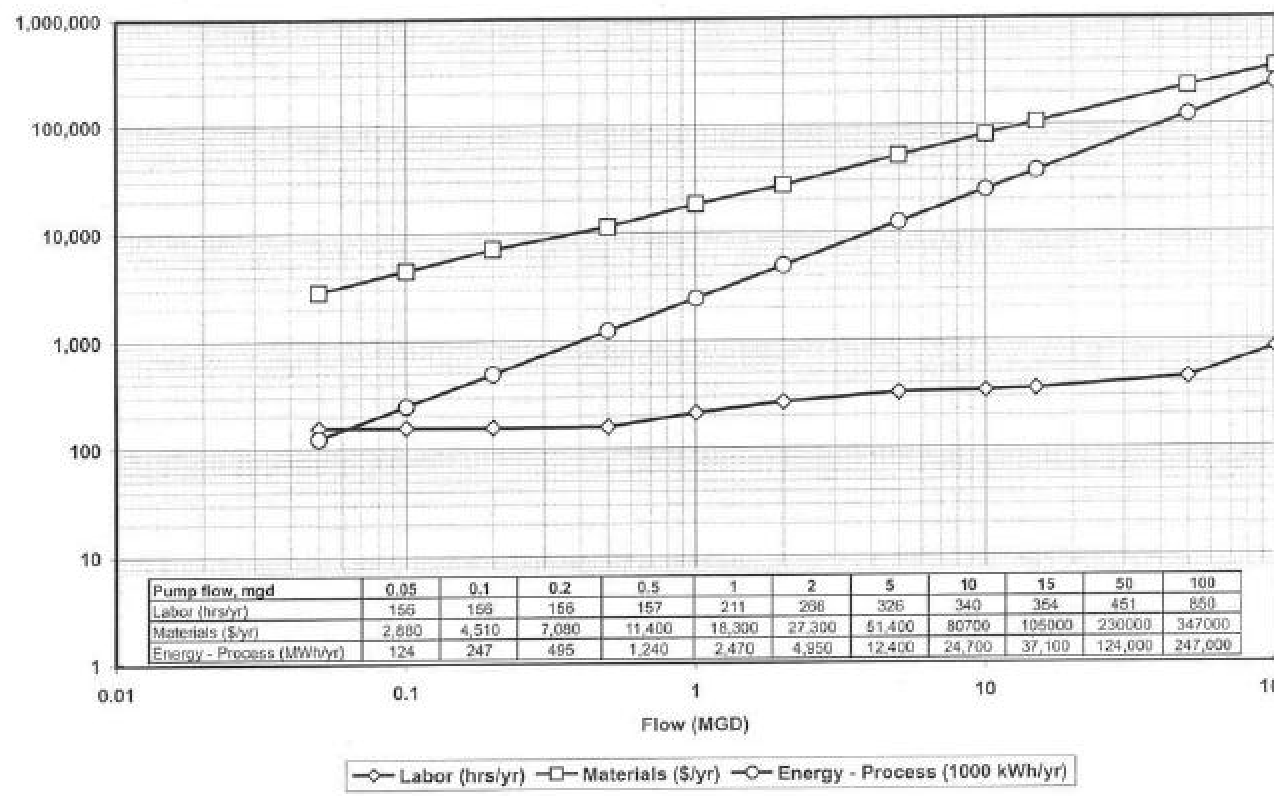
Pump flow (MGD)	0.05	0.1	0.2	0.5	1	2	5	10	20	50	100
Labor (hrs/yr)	156	156	156	157	211	214	274	340	420	607	850
Materials ($/yr)	1,660	2,600	4,080	6,550	10,500	16,500	28,600	46,500	69,000	121,000	200,000
Energy - Process (MWh/yr)	53	106	212	530	1,060	2,120	5,300	10,600	21,200	53,000	106,000

Figure 74. O&M Costs for Membrane Feed Pumping (Low Pressure, 300 psi) (after HDR and others, 2000)



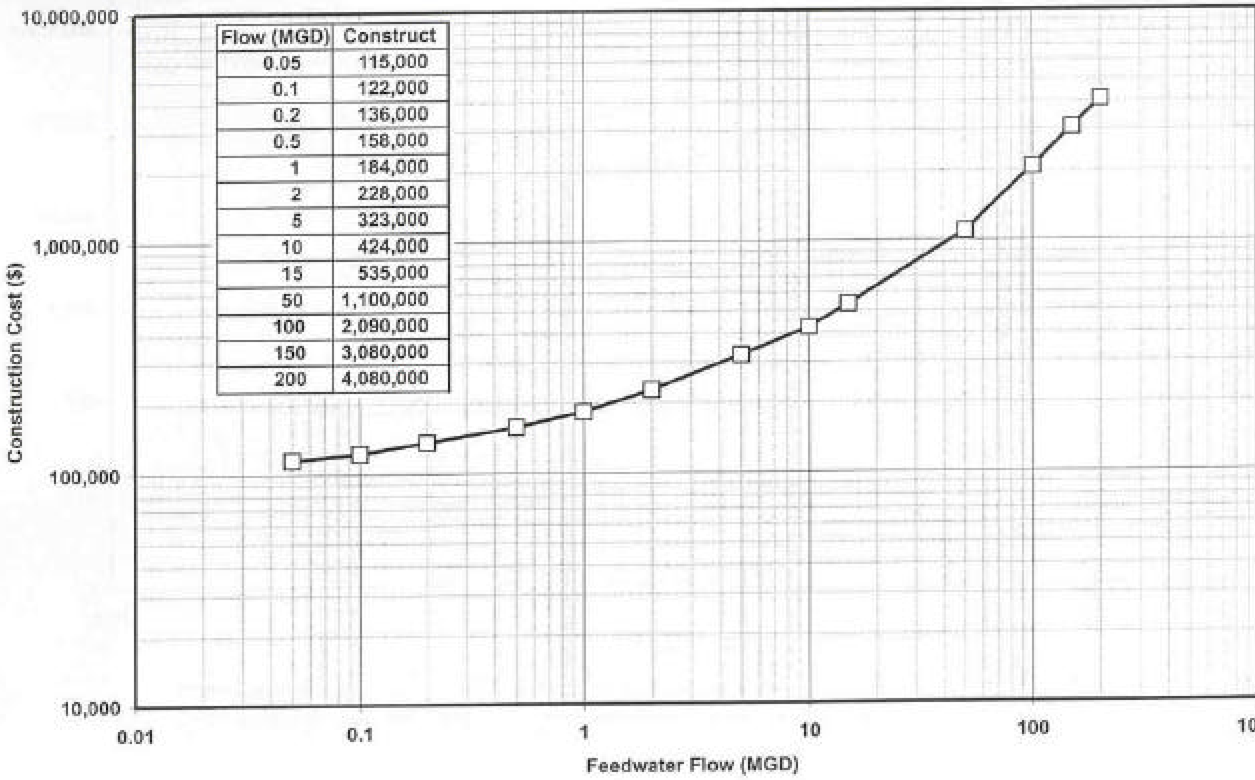
Pump flow (MGD)	0.05	0.1	0.2	0.5	1	2	5	10	15	50	100
Labor (hrs/yr)	156	156	156	157	211	266	328	340	354	451	850
Materials ($/yr)	2,310	3,630	5,690	9,130	14,700	21,900	41,300	64,800	84,400	185,000	279,000
Energy - Process (MWh/yr)	88	177	354	884	1,770	3,540	8,840	17,700	26,500	88,400	177,000

Figure 75. O&M Costs for Membrane Feed Pumping (Medium Pressure, 500 psi)
(after HDR and others, 2000)



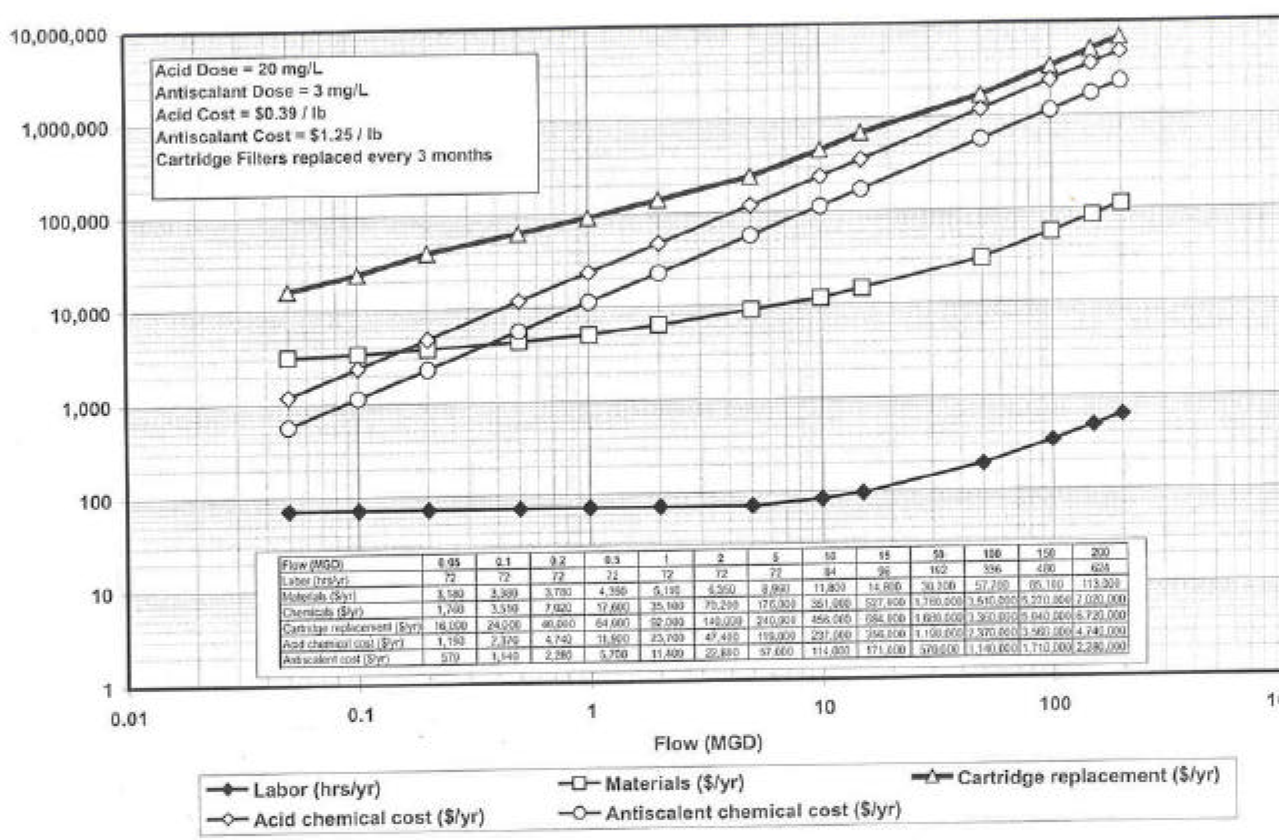
Pump flow, mgd	0.05	0.1	0.2	0.5	1	2	5	10	15	50	100
Labor (hrs/yr)	156	156	156	157	211	266	326	340	354	451	850
Materials ($/yr)	2,880	4,510	7,080	11,400	18,300	27,300	51,400	80700	105000	230000	347000
Energy - Process (MWh/yr)	124	247	495	1,240	2,470	4,950	12,400	24,700	37,100	124,000	247,000

Figure 76. O&M Costs for Membrane Feed Pumping (High Pressure, 700 psi)
(after HDR and others, 2000)



Flow (MGD)	Construct
0.05	115,000
0.1	122,000
0.2	136,000
0.5	158,000
1	184,000
2	228,000
5	323,000
10	424,000
15	535,000
50	1,100,000
100	2,090,000
150	3,080,000
200	4,080,000

Figure 77. Construction Costs for Reverse Osmosis Pretreatment
(after HDR and others, 2000)



Flow (MGD)	0.05	0.1	0.2	0.5	1	2	5	10	15	50	100	150	200
Labor (hrs/yr)	72	72	72	72	72	72	72	84	96	162	336	480	624
Materials ($/yr)	3,180	3,380	3,780	4,350	5,190	6,350	8,990	11,800	14,800	30,300	57,200	85,100	113,000
Chemicals ($/yr)	1,760	3,510	7,020	17,600	35,100	70,200	176,000	351,000	527,000	1,760,000	3,510,000	5,270,000	7,020,000
Cartridge replacement ($/yr)	16,000	24,000	40,000	64,000	92,000	140,000	240,000	456,000	684,000	1,680,000	3,360,000	5,040,000	6,720,000
Acid chemical cost ($/yr)	1,190	2,370	4,740	11,900	23,700	47,400	119,000	237,000	356,000	1,190,000	2,370,000	3,560,000	4,740,000
Antiscalent cost ($/yr)	570	1,140	2,280	5,700	11,400	22,800	57,000	114,000	171,000	570,000	1,140,000	1,710,000	2,280,000

Figure 78. O&M Costs for Reverse Osmosis Pretreatment
(after HDR and others, 2000)

high (700 psi) pressure requirements. Each of the graphs show the individual O&M components, including labor, materials, and energy costs. Some conclusions can be drawn from these figures. First, material and energy costs are the largest O&M expenses. While there is a slight economy of scale regarding materials with increased production rates, there is no economy gained regarding energy costs with larger production facilities. For the low pressure systems (300 psi) producing 10 MGD, the required energy is 10,600 megawatt-hours per year (MWh/yr). For a 500-psi system, the energy increased 77% to 17,700 MWh/yr, and for a 700-psi system, the energy requirements would increase 125% to 24,700 MWh/yr. These relationships indicate the significant energy savings that can be achieved by treating low TDS groundwater as opposed to saline groundwater or seawater.

4.2.5 Pretreatment Costs

Reverse osmosis systems may require pretreatment of the feedwater (brackish groundwater) to adjust pH and prevent salt scaling. Cartridge filters are usually employed to remove particulates that might foul, clog or damage membranes. In addition, there is equipment required for these pretreatment systems. Figure 77 graphically summarizes the construction costs for pretreatment systems based on the feedwater flow. As indicated by the graph, there is an economy of scale in the construction costs for the pretreatment systems. Figure 78 shows the relationship between several O&M cost components associated with RO pretreatment at various production rates. As expected, the figure indicates that there is a significant economy of scale in labor and material costs, and somewhat less economy of scale in chemical and cartridge costs. Pretreatment costs are generally higher for surface water (brackish lakes and seawater) than for brackish groundwater because of the need for pretreatment filtration.

4.3 Cost of Wells for Source Water

Cost estimates required for water management strategies that include additional wells or well fields can be roughly estimated from the relationships in Table 7. These cost relationships are "rule-of-thumb" in nature and are meant to be used only in the broad context of the cost evaluations for the RWP process. The cost relationships assume construction methods required for public water supply wells, including carbon steel surface casing and pipe-based, stainless steel, and wire-wrap screen. The cost estimates assume that wells would be gravel-packed in the screen sections and the surface casing cemented to their total depth. In addition, the cost estimates include the cost of drilling, completion, well development, well testing, pump, motor, motor controls, column pipe, installation and mobilization. The cost relationships do not include engineering, contingency, financial and legal services, land costs, or permits. A more detailed cost analysis should be completed prior to developing a project.

The generic cost relationships are developed for wells of different well casing diameter. A cost relationship was developed for wells ranging from 6 to 16 inches in diameter and each relationship includes the variables for discharge and well depth. The pump costs assume that the pump is set at 300 feet below ground surface and that the lift is 300 feet. Pump depth and lift requirements will vary in each situation and may need to be adjusted for individual projects.

Table 7. Estimated Well Costs for Brackish Water Production Wells

Well Diameter (inches)	Typical Production Range (gpm)	Estimated Cost (2002 $) a=production rate (gpm), b= well depth (feet)
6	25-150	7000 + 68a + 60b
8	150-300	10000 + 65a + 140b
10	300-500	15000 + 63a + 180b
12	500-800	20000 + 60a + 225b
16	800-2000	22000 + 60a + 320b

Using the cost relationships in Table 7, a 700-gpm well with a total depth of 1,000 feet would cost approximately $305,000.

The costs associated with conveyance systems for multi-well systems can vary widely based on the distance between wells, terrain characteristics, well production, and distance to the treatment or brine disposal facility. These costs should be estimated using standard engineering approaches and site-specific information.

4.4 Concentrate Disposal

Concentrate disposal methods and processes are a major element in the overall cost of the desalination process. The method used to dispose of concentrate is a major decision in designing and planning the overall desalination strategy. The ability to estimate the quantity and quality of the concentrate stream allows proper selection of the disposal process and subsequent regulatory permitting.

HDR and others (2000) identify potential approaches for brine disposal and the typical requirements for obtaining regulatory approval for brine disposal. These approaches include surface water discharge, pre-discharge mixing, discharge to municipal wastewater systems, deep well injection, and land application.

Table 8 (after HDR and others, 2000) summarizes the potential advantages and constraints for different types of brine disposal. The major cost considerations for each of these brine disposal methods is also discussed by HDR and others (2000). However, it is difficult to estimate generic disposal cost relationships because the options vary significantly between projects. Prior to project implementation, a thorough review of pertinent regulations regarding brine disposal and associated water quality issues should be completed to ensure that proposed brine disposal methods and cost estimates are appropriate for planning purposes.

Table 8. Concentrate Disposal Options Summary (after HDR and others, 2000)

Disposal Option	*Advantages*	*Constraints*
Brackish Desalination		
1. Direct surface water discharge	• Low cost up front	• Requires available receiving water body • Future regulations may restrict • Monitoring program
2. Pre-discharge mixing	• Low to medium cost up front	• Requires adequate mixing source • Monitoring program
3. Municipal wastewater system	• Low cost (if co-located) • Additional source for reclaimed water	• Higher wastewater treatment costs • Impacts to treatment process
4. Deep well injection	• Can handle large volume • May be available to inland plants	• Difficult permitting, high up front cost
5. Land Application	• Best suited for small facilities	• Difficult to site

In the following sections, methods of estimating costs for brine disposal are discussed.

4.4.1 Cost Estimates for Brine Disposal Methods

USBR (2001) documented membrane concentrate disposal practices and the regulations that impact disposal systems and techniques. This report was based on the findings from a detailed survey of 149 membrane plants that included 84% of the utility desalting plants (RO, EDR, and nanofiltration) built in the United States between 1993 and 1999. The survey also included 44% of the utility low-pressure membrane (microfiltration and ultrafiltration) plants built during the same period. The report describes cost considerations for concentrate disposal to deep well injection, evaporation ponds, spray irrigation, and zero liquid discharge. Findings of the report regarding disposal via deep-well injection and evaporation ponds are included here as a reference for planners who need to complete preliminary cost analysis. For more details on cost estimation of spray irrigation and zero liquid discharge, please see USBR (2001).

4.4.1.1 Deep Well Injection Cost Estimates

The costs of disposal by deep-well injection are subject to many site-specific circumstances – perhaps more so than those of any other disposal method (USBR, 2001). Potential costs variables include those associated with site terrain, availability of water for drilling and injection testing, subcontractors, geology, drilling difficulty, regulatory issues, and others. USBR (2001) describes a regression cost model to determine the total capital cost for injection wells based on 35 case studies. It should be noted that most of these wells where located in Florida, and the reader should be aware of any differences which may affect these estimates by referring to the original USBR (2001) report. The simple formulation for estimating total capital cost for deep-well disposal is shown in Equation 2 below.

$$CC = -288 + 145.9(TD) + 0.754(D) \qquad \text{(Equation 2)}$$

where:

CC = total capital cost (x $1,000)
TD = tubing diameter (inches)
D = depth (feet)

Figure 79 shows the relationship between total capital cost for deep-well disposal, well depth, and tubing diameter. For most cost models, the size of the disposal option is based on flow rate of concentrate. For deep-well disposal this is not always the case. Because the material costs are not the major cost factor for the deep injection wells, there is relatively little penalty or additional cost for designing and building a well capable of receiving larger flows. This might be done to allow for future plant expansion or for future shared use of the well. If the tubing and packer requirements were not necessary for disposal of membrane concentrate, the tubing could be removed, resulting in a much larger capacity deep injection well – limited by the diameter of the final casing string (USBR, 2001).

It should be noted that the cost model and regression cost equation are provided only to obtain a preliminary level cost estimate. Site-specific conditions might significantly change estimates for the injection well disposal costs. The availability of suitable subsurface injection zones is a critical issue to be evaluated if deep well disposal is anticipated for a desalination plant.

4.4.1.2 Evaporation Pond Cost Estimates

Evaporation ponds are a well established method for removing water from a concentrate solution, especially in arid climates. Evaporation ponds for membrane concentrate disposal are most appropriate for smaller volume flows and for regions with relatively high evaporation rates, level topography, and low land costs.

Advantages of evaporation ponds include (after USBR, 2001):

- Relatively easy to design and construct.
- Properly constructed evaporation ponds are low maintenance and require little operator attention compared to mechanical equipment and approaches.
- Very little mechanical equipment is required except for pumps to convey concentrate to the evaporation ponds.
- For small volumes of concentrate, evaporation ponds are often the least expensive means of disposal.

Disadvantages may include:

- Requirement for large tracts of land to facilitate evaporation ponds.
- Requirement for clay or synthetic liners, which may increase the construction costs. Leaking ponds can cause groundwater contamination.
- There is little economy of scale due to the nature of the evaporation process, and thus, large flows, expensive land, or uneven terrain can increase the total concentrate disposal costs.

The criteria for high evaporation rates are better met in the western half of Texas than in the eastern portion of the state. Design and cost considerations for evaporation

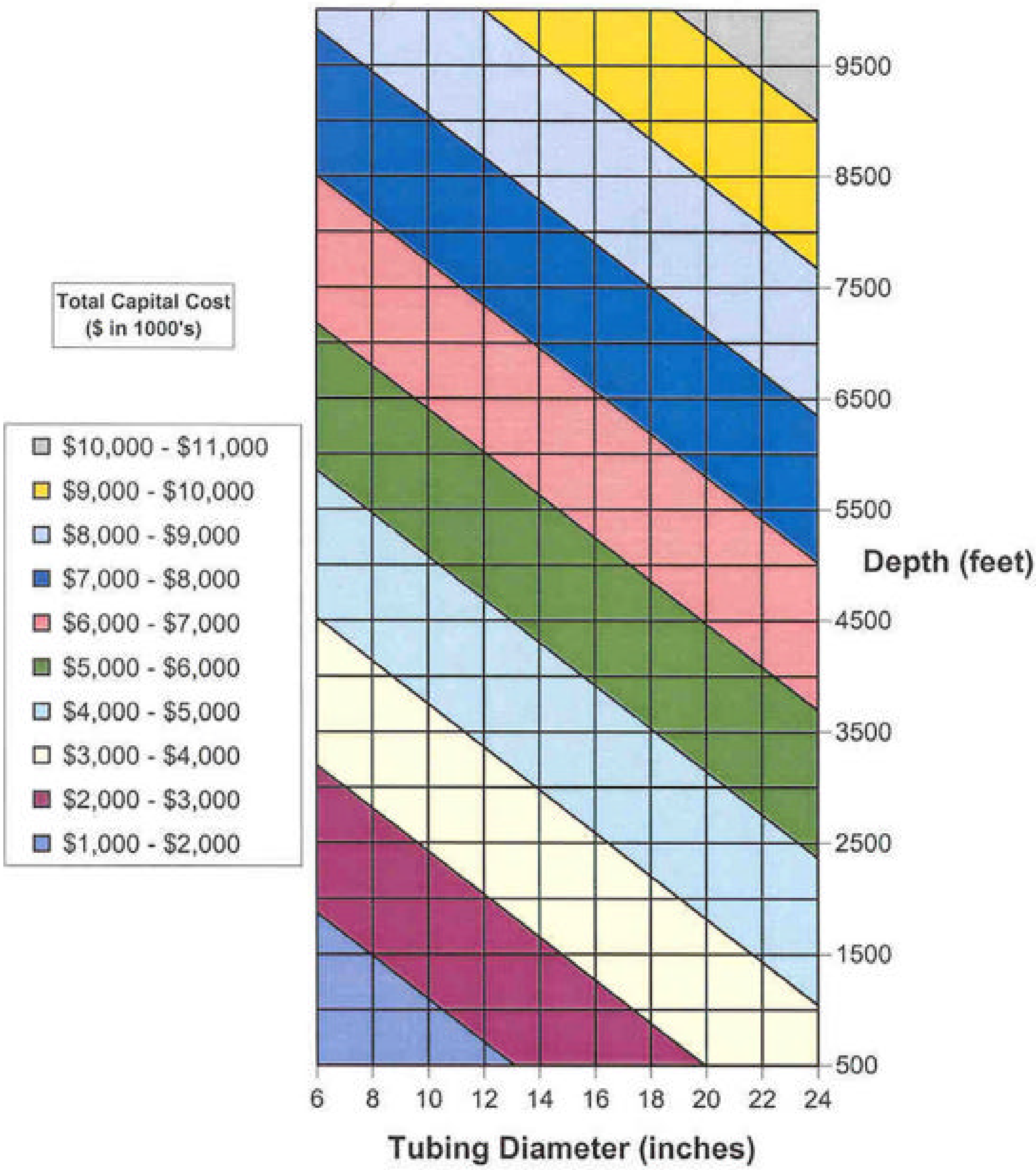


Figure 79. Total Concentrate Disposal Cost as a Function of Tubing Diameter and Well Depth (after USBR, 2001)

ponds include determination of the evaporation rate, pond depth, land clearing, dike construction, liner materials and construction, miscellaneous costs (fencing, roads, seepage monitoring, etc.), operations, pond maintenance, and potential sludge removal. Of course, the first variable to be determined for proper sizing of evaporation ponds is the evaporation rate at the proposed facility location. The TWDB maintains an historical database of evaporation estimates for the entire state of Texas since 1940. Design and cost calculations should consider these data when making estimates of the pond area that will be required to use evaporation as the concentrate disposal method. After the appropriate pond area has been determined, the following formulas can be used to estimate capital cost for constructing an evaporation pond disposal system. If there is significant seasonal changes in evaporation rates, this variation would need to be incorporated into the design.

USBR (2001) developed a simple formulation for estimating the total area (TA) required for the operation (with 20% contingency incorporated) can be estimated by:

$$TA = 1.2(EA)[1 + 0.155(DH)/\mathrm{sqrt}(EA)] \qquad \text{(Equation 3)}$$

where:

- TA = total area (acres)
- EA = evaporation area (acres)
- DH = dike height (feet)

The total unit area capital cost for evaporation pond disposal is shown in Equation 4:

$$UC = 5406 + 465(LT) + 1.07(LC) + 0.93(CC) + 217.5(DH) \qquad \text{(Equation 4)}$$

where:

- UC = total unit area capital cost ($/acre)
- LT = liner thickness (millimeters)
- LC = land cost ($/acre)
- CC = land clearing cost ($/acre)
- DH = dike height

The total capital cost is determined by multiplying TA by UC.

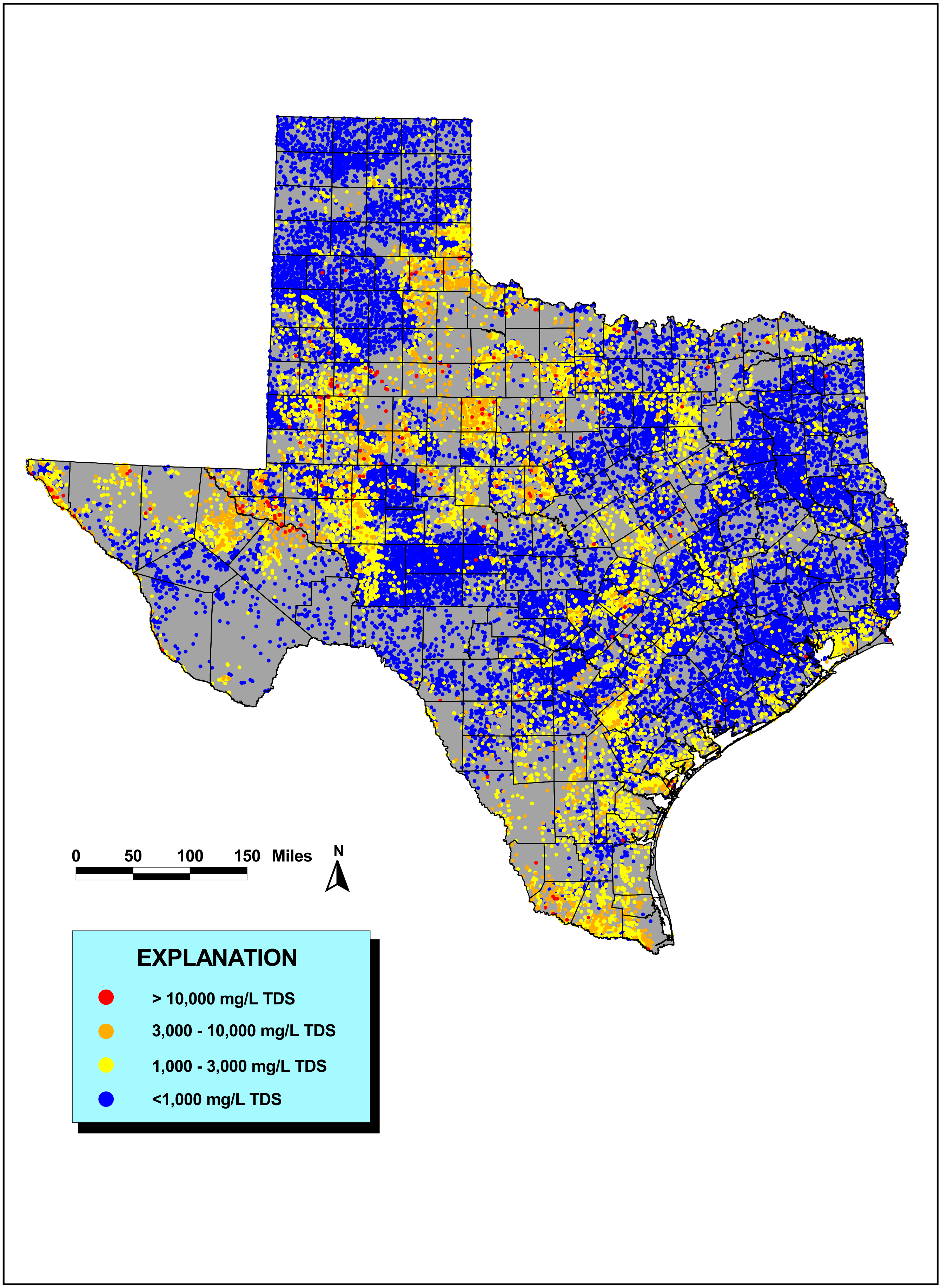
5.0 SUMMARY AND CONCLUSIONS

The State of Texas has a tremendous resource in brackish groundwater throughout the state. Increasing water demands, increasing water rights costs, decreasing freshwater supplies, stricter drinking water standards, and more cost-effective desalination technology are paving the way for more widespread and cost-effective use of this resource. Proper assessment of potential implementation strategies for using brackish groundwater requires a basic understanding of the hydrogeologic setting of the brackish groundwater, infrastructure requirements to produce, treat, and convey the water, concentrate disposal methods, and potential impacts of brackish groundwater production. This document has been developed to assist planners in identifying and assessing potential brackish groundwater resources as well as developing preliminary cost estimates for proposed strategies. Although the report is general in nature, and typically provides regional hydrogeologic perspectives, it can serve as a valuable tool to help identify potential brackish groundwater and aid in developing cost comparisons for RWPAs and other planning entities. This document it is not intended to be an exhaustive resource on the subject of brackish groundwater resources and desalination of brackish groundwater in Texas, and it should be understood that any proposed desalination project will require site-specific hydrogeologic and engineering analysis.

Some water suppliers are considering brackish groundwater desalination as a means to increase their water treatment capacity with the side benefit of using an alternative water supply and improving, in most cases, the water quality for their customers. In areas where the cost of water rights are high for surface water, the purchase of surface water rights can be more than the capital cost of a brackish desalination plant of the same capacity. Conversely, others look at this methodology to increase their supply with the side benefit of having additional treatment capacity.

This report focuses on slightly- to moderately-saline groundwater, which contains between 1,000 mg/L and 10,000 mg/L TDS. This range was selected because it represents the most economically feasible type of non-fresh water to treat for public water supply purposes. Because this report does not assess saline groundwater (greater than 10,000 mg/L TDS), many of the deeper saline aquifers and down-dip portions of freshwater aquifers are not considered or discussed.

Figure 80 shows all of the TDS data that was compiled fro this report from the TWDB database for the entire State of Texas. This figure illustrates that there are many areas in the state that have a significant percentage of brackish groundwater. Although many areas of the State contain some brackish groundwater, areas containing significant brackish groundwater include West Texas, North-Central Texas, Central Texas, and the Southern Coastal region. Brackish groundwater resources may be especially important in planning and future development for the north-central and western portions of the state, where new surface water supplies are limited or nonexistent. This fact has already been demonstrated in the current development of a desalination plant for the treatment of brackish groundwater from the Hueco Bolson aquifer for use in El Paso. In the Southern Coastal region, brackish groundwater from the Gulf Coast aquifer has already been developed as a desalination source for use in the Brownsville area. These projects demonstrate that there is a real demand and economical use for brackish groundwater in



GROUNDWATER QUALITY
IN THE STATE OF TEXAS

FIGURE 80

LBG-GUYTON ASSOCIATES

certain areas of the state. However, the potential role of brackish groundwater as a cost effective supply in other areas where fresh groundwater is available should not be underestimated. For example, small water user groups that are still heavily dependent on groundwater may find that brackish groundwater is a readily available source for desalination if fresh groundwater supplies are depleted or if water quality of existing sources degrades and economical surface-water supplies are not available.

Recent data have shown that the cost of brackish groundwater desalination is decreasing and that improved membrane technology is still increasing the efficiency and effectiveness of the desalination process. The cost information summarized in this report indicates that the total treatment cost of brackish groundwater desalination can range from $1.50/Kgal to $2.75/Kgal. In general, it is less expensive to desalinate lower TDS groundwater than higher TDS brackish groundwater because the energy requirements for desalination of low TDS water are less than for high TDS water. Because energy costs are a major component of O&M cost of desalination facilities, significant cost savings can be achieved by reducing energy costs. The estimated cost of brackish groundwater desalination needs to consider more than the plant itself. Groundwater production costs and disposal costs should also be considered in the overall cost. Cost comparisons between various strategies should include all components of each strategy and should be based on site-specific information to the degree possible.

Source-water production, concentrate disposal, and plant design should be considered simultaneously throughout project conceptualization and design because each component of the project is interrelated. Hydrogeologic and engineering components of a brackish groundwater desalination strategy are not mutually exclusive and will require coordinated planning to achieve the best results. For example, hydrogeologic reconnaissance, test drilling, and well construction can significantly impact the water quality of the resulting feedwater for a desalination facility. The design of the treatment plant, including membrane design and other engineering factors are influenced by the source-water quality, and in turn can influence the water quality of the concentrate from the desalination process, which impacts the concentrate disposal planning, methodology, and cost. Disposal of concentrate from desalination of brackish groundwater is a major consideration in planning a brackish groundwater desalination strategy and properly estimating the cost of the strategy.

Table 9 provides a summary of the brackish groundwater resources in each RWPA by aquifer in Texas. As described in Section 2.2., brackish groundwater was characterized and scored according to availability, productivity, and source-water production cost. This summary indicates that there is significant brackish groundwater available in many RWPAs and aquifers in Texas. In many areas, the estimated productivity of the brackish portions of the aquifers is capable of meeting small- to medium-sized demands and in some areas, may be capable of meeting large demands. Source-water production costs vary between brackish groundwater sources because of the depth to brackish groundwater and/or the productivity of wells.

Brackish groundwater resources offer the State of Texas a potential source of water that has not been fully utilized in the past. Each RWPG should consider strategies that use brackish groundwater as a way of meeting future demands.

Table 9. Summary of Brackish Groundwater Resources in Each Regional Water Planning Area

Region	Aquifer	Status of Brackish Groundwater		
		Availability	Productivity	Source Water Production Cost
A- Panhandle	Seymour	Low	Moderate	Low
	Blaine	High	Low to Moderate	Moderate
	Dockum	Low	Low	Low
	Ogallala	Low	High	Low to Moderate
	Rita Blanca	Low	Low to Moderate	Moderate
	Whitehorse-Artesia	High	Low to Moderate	Moderate
B- Region B	Seymour	Moderate	Moderate	Low
	Blaine	High	Low to Moderate	High
	Trinity	None	--	--
	River Alluviums	Moderate	High	Moderate
	Whitehorse-Artesia	Unknown	Low to Moderate	Moderate
C- Region C	Nacatoch	Low	Low	Moderate to High
	Queen City and Sparta	None	--	--
	Carrizo-Wilcox	None	--	--
	Trinity	Moderate	Low	Moderate to High
	Woodbine	High	Low to Moderate	Moderate to High
D- North East Texas	Nacatoch	Low to Moderate	Low	Moderate
	Queen City and Sparta	Moderate	Low	Moderate
	Blossom	Low	Low	Moderate
	Woodbine	Low	Low to Moderate	Moderate to High
	Trinity	None	--	--
	Carrizo-Wilcox	High	Moderate	Moderate to High
E- Far West Texas	Rustler	Low to Moderate	Low	Moderate
	Bone Spring/Victorio Peak	High	High	Low to Moderate
	Capitan Reef Complex	High	High	Moderate
	Edwards-Trinity (Plateau)	None	--	--
	Hueco Bolson	High	Moderate	Moderate
	Mesilla Bolson	High	Moderate	Low to Moderate
	Igneous	None	--	--
	Marathon	Unknown	Unknown	Unknown
	River Alluviums	High	High	Low to Moderate
	West Texas Bolsons	Moderate	Moderate	Moderate

Table 9. Summary of Brackish Groundwater Resources in Each Regional Water Planning Area

Region	Aquifer	Status of Brackish Groundwater		
		Availability	Productivity	Source Water Production Cost
F- Region F	Rustler	High	Low to High	Moderate to High
	Lipan	High	Moderate	Low to Moderate
	Blaine	Unknown	Unknown	Unknown
	Capitan Reef Complex	High	High	Moderate
	Cenozoic Pecos Alluvium	High	High	Moderate
	Dockum	Moderate	Low	High
	Edwards-Trinity (High Plains)	None	--	--
	Edwards-Trinity (Plateau)	High	Low	Low
	Ellenburger-San Saba	Moderate	Moderate	Moderate to High
	Hickory	Moderate	Moderate	Moderate to High
	Marble Falls	Low	Unknown	Moderate to High
	Ogallala	Moderate	High	Low to Moderate
	Trinity	Low	Low	Low
	River Alluviums	Moderate	High	Moderate
	Whitehorse-Artesia	Moderate	Low to Moderate	Moderate
G- Brazos	Edwards (BFZ)	Moderate	Low to Moderate	Moderate to High
	Queen City and Sparta	Moderate	Low	Moderate to High
	Seymour	Moderate	Moderate	Low
	Blaine	Low	Low to Moderate	Moderate
	Carrizo-Wilcox	High	Moderate	Moderate to High
	Edwards-Trinity (Plateau)	None	--	--
	Ellenburger-San Saba	Low	Moderate	Moderate
	Trinity	Moderate	Moderate	Moderate to High
	Hickory	Unknown	Moderate	Moderate to High
	Marble Falls	Low	Unknown	Moderate to High
	River Alluviums	High	High	Low
	Whitehorse-Artesia	Unknown	Low to Moderate	Moderate
	Woodbine	Moderate	Low to Moderate	Moderate to High
	Yegua-Jackson	Moderate	Low	Moderate to High
H- Region H	Queen City and Sparta	Moderate	Low	Moderate to High
	Carrizo-Wilcox	Moderate	Moderate	Moderate to High
	Gulf Coast	High	High	Low to Moderate
	Yegua-Jackson	Moderate	Low	Moderate
I- East Texas	Queen City and Sparta	High	Low	Moderate
	Carrizo-Wilcox	High	Moderate	Moderate to High
	Gulf Coast	High	High	Low to Moderate
	Yegua-Jackson	Moderate	Low	Moderate
J- Plateau	Edwards (BFZ)	Low to Moderate	Low to Moderate	Moderate to High
	Edwards-Trinity (Plateau)	Unknown	Unknown	Unknown
	Trinity	Moderate	Low	Moderate to High
	Ellenburger-San Saba	Low	Moderate	High
	Hickory	Unknown	Moderate	Moderate to High
	Marble Falls	Low	Unknown	Moderate to High

Table 9. Summary of Brackish Groundwater Resources in Each Regional Water Planning Area

Region	Aquifer	Status of Brackish Groundwater		
		Availability	Productivity	Source Water Production Cost
K- Lower Colorado	Edwards (BFZ)	Low to Moderate	Low to Moderate	Moderate to High
	Queen City and Sparta	Moderate	Low	High
	Carrizo-Wilcox	High	Moderate	Moderate to High
	Edwards-Trinity (Plateau)	None	--	--
	Ellenburger-San Saba	Moderate	Moderate	Moderate to High
	Gulf Coast	Moderate to High	High	Low to Moderate
	Trinity	Moderate	Low	Moderate to High
	Hickory	Low	Moderate	Moderate to High
	Marble Falls	Low	Unknown	Moderate to High
	Yegua-Jackson	Moderate to High	Low	Moderate to High
L- South Central Texas	Edwards (BFZ)	High	Low to Moderate	Moderate to High
	Queen City and Sparta	Moderate to High	Low	Moderate to High
	Carrizo-Wilcox	High	High	Moderate to High
	Edwards-Trinity (Plateau)	None	--	--
	Ellenburger-San Saba	Low	Moderate	High
	Gulf Coast	Moderate	High	Low
	Trinity	Moderate	Low	Moderate to High
	Hickory	Unknown	Moderate	Moderate to High
	Marble Falls	Low	Unknown	Moderate to High
	Yegua-Jackson	Moderate to High	Low	Moderate to High
M- Rio Grande	Queen City and Sparta	High	Moderate	Moderate
	Carrizo-Wilcox	Low	Low	High
	Gulf Coast	Moderate	Moderate	Low to Moderate
	River Alluviums	High	High	Moderate
	Yegua-Jackson	High	Low	Moderate
N- Coastal Bend	Queen City and Sparta	Low	Low	High
	Carrizo-Wilcox	Low	Moderate	High
	Gulf Coast	Moderate	Moderate to High	Low
	Yegua-Jackson	Low	Low	Moderate to High
O- Llano Estacado	Seymour	Unknown	Unknown	Unknown
	Dockum	Low	Low	Moderate to High
	Edwards-Trinity (High Plains)	High	Low	Moderate
	Ogallala	High	High	Low to Moderate
	Whitehorse-Artesia	Moderate	Low to Moderate	Moderate
P- Lavaca	Carrizo-Wilcox	None	--	--
	Gulf Coast	Low	High	Low
	Yegua-Jackson	Low	Low	High

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APPENDIX A

GROUNDWATER TERMINOLOGY AND GLOSSARY

This report describes the brackish groundwater resources for the State of Texas, and there are some terms and concepts typically used to describe these resources that may not be understood by every user of this report. This section gives a very brief overview of some of the basic concepts of hydrogeology, a description of some of the terms used in this report, and a definition of some of the terminology that may be found in the descriptions in this report.

General Hydrogeology Terms

Aquifer- A rock formation that contains sufficient water to be economically produced to wells is typically referred to as an aquifer.

Aquitard or Confining Unit- A rock formation that is relatively impermeable and serves to restrict the vertical movement of water from an aquifer located above or below. In some cases aquitards are capable of producing groundwater to very small wells, but they are generally not used as a groundwater source.

Unconfined or Water Table Aquifer- An aquifer whose upper boundary is formed by the water table. Typically found in the uppermost sediments at relatively shallow depths, unconfined aquifers produce water by the actual dewatering of the void space in the aquifer.

Confined or Artesian Aquifer- An aquifer that is confined below an overlying aquitard. In most cases the water level in a well producing from a confined aquifer rises above the top of the aquifer and in some cases may be hundreds of feet above the actual aquifer. Where the water level in a well is higher than land surface, a "flowing artesian well" occurs.

Outcrop- An aquifer's outcrop is where the rocks that make up an aquifer occur at land surface. In some aquifers, in particular for alluvial aquifers, the entire aquifer occurs only under the outcrop. In many cases, however, the outcrop is only a small portion of the extent of an aquifer, and most of the aquifer is found in the subsurface beneath other rock formations. The outcrop is important to an aquifer because this is where most of the recharge via the infiltration of precipitation occurs.

Down-dip- The term "down-dip" is often used to refer to areas of an aquifer or geologic formation that occur farther down in the subsurface from the outcrop. This term is especially important in the study of brackish groundwater because it is often in the down-dip areas that brackish groundwater is found in an aquifer.

Recharge- Recharge is the process of adding water to an aquifer. Most aquifers get much of their recharge through the infiltration of precipitation on the outcrop area of the aquifer. In addition, recharge can occur through the infiltration of water from lakes, streams, and rivers that cross the outcrop area, and by the flow of groundwater from another aquifer that either overlies or underlies an aquifer.

Discharge- Discharge is the loss of water from an aquifer. Historically, before aquifers were developed, discharge occurred through evapotranspiration (the loss of water to plants and evaporation), flow to local seeps, springs, streams, and rivers, and through cross-formational flow to overlying or underlying aquifers. As the development of an aquifer occurs, pumping of wells may become the predominant method of discharge.

Hydraulic Gradient- Groundwater flows from areas with higher water levels to areas with lower water levels (i.e. downgradient). The hydraulic gradient is a term used to describe the steepness of the slope of the aquifer's water-table surface, and may be expressed as units of feet per mile (ft/mi). The term "upgradient" refers to areas in an aquifer with higher water levels, and "downgradient" refers to areas with lower water levels.

Well Yield- The rate of production or capacity of a well is called the well yield and is described in terms of gallons per minute (gpm).

Aquifer Characteristics

Several factors are used to describe groundwater flow in aquifers and the ability of a well to produce water from an aquifer. These include porosity, hydraulic conductivity, transmissivity, coefficient of storage or storativity, specific yield, and specific capacity. Each of these terms is briefly described below.

Porosity- The volume of voids divided by total volume of material in an aquifer equals the porosity of the aquifer. This describes the amount of space capable of being filled with gas or fluids, and is typically expressed as percent.

Hydraulic Conductivity- The measure of the ease with which groundwater can flow through an aquifer, also referred to as permeability (or coefficient of permeability). Higher hydraulic conductivity indicates that the aquifer will allow more water movement under the same hydraulic gradient. Units for hydraulic conductivity may be expressed in feet/day or gallons/day/foot^2 (gpd/ft^2). The latter units will be used in this report.

Transmissivity- This term is closely related to hydraulic conductivity and refers to the product of the hydraulic conductivity multiplied by the thickness of the aquifer. Transmissivity describes the ability of groundwater to flow through the entire thickness of an aquifer. As the thickness of the aquifer increases, the transmissivity increases. Units for transmissivity may be expressed in feet^2/day or gallons/day/foot (gpd/ft). The latter units will be used in this report.

Storativity- Also referred to as the coefficient of storage, this term describes the volume of water a confined aquifer will release when the water level (also called the potentiometric surface) in an aquifer is lowered.

Specific Yield- Specific yield is used to describe the amount of water an unconfined aquifer will yield per unit decline in the water level in an aquifer. Water produced from unconfined aquifers is produced by dewatering the void space in an

Specific Capacity- This is a term that is used to measure the efficiency of a well and an aquifer to produce water to a well. This term is dependent on both the properties of the aquifer as well as the efficiency of the well. Wells in the same aquifer can have different specific capacities due to differences in well construction including well diameter, borehole diameter, type of sand or gravel-pack used, size and type of screen used, gravel-pack or well screen clogging, etc. Specific capacity is expressed in terms of gallons per minute per foot of drawdown in the well (gpm/ft).

Water Quality Descriptions

Water quality for groundwater can be described using a variety of chemical parameters. A commonly used parameter to describe the overall groundwater quality is total dissolved solids or TDS. This is the parameter that describes the sum of all of the dissolved constituents in water. The major components included are calcium, magnesium, sodium, chloride, sulfate, and bicarbonate. Some of the minor parameters include potassium, nitrate, iron, and fluoride, as well as numerous other trace constituents. For this report, TDS will be used as the description of groundwater quality.

TDS will be described in units of milligrams per liter (mg/L). This refers to the mass of the dissolved solids, in milligrams, per liter of water. The units of mg/L are commonly interchanged with parts per million (ppm). Several terms are used to generically describe water or groundwater.

Fresh- is used to describe water containing less than 1,000 mg/L TDS.

Slightly-saline- is used to describe water containing between 1,000 and 3,000 mg/L TDS.

Moderately-saline- is used to describe water containing between 3,000 and 10,000 mg/L TDS.

Saline- is used to describe water containing greater than 10,000 mg/L TDS.

Brackish- as used in this report, is used to describe either slightly- or moderately-saline groundwater, and thus any water containing 1,000 to 10,000 mg/L TDS is referred to as brackish groundwater.

The relationship between the terms described above is illustrated below. The colors used in the chart below are also those used in the figures in the aquifer descriptions and in the cross sections.

	1,000 mg/L	3,000 mg/L	10,000 mg/L
Fresh	Brackish		Saline
Fresh	Slightly-saline	Moderately-saline	Very-saline

Other Terms Used in This Report

Karst- This term is used to describe the dissolution of limestone, dolomite, and gypsum rocks which forms sinkholes, caves, and underground conduits. This is important in hydrogeology because karst aquifers that occur in karst environments may produce large amounts of water from the caves and other conduits that occur in the aquifer.

Solution (or Dissolution) Channel- This term refers to a conduit or other type of feature that occurs in an aquifer when the aquifer rock formation dissolves in the groundwater that passes through the aquifer.

Subsidence- Subsidence is a drop in the land-surface that occurs when an aquifer begins to compress when water is removed (pumped) from it. Subsidence has occurred in areas where the Gulf Coast Aquifer System has been heavily pumped.

Geologic Ages- Geologic ages are included in the individual aquifer descriptions. These are summarized in the following table.

Summary of Geologic Ages of Texas Aquifers
(after Ashworth and Hopkins, 1995)

Age (million years ago)	Era	Period	Aquifer
2	Cenozoic	Quaternary	Cenozoic Pecos Alluvium River Alluvium Seymour West Texas Bolsons Lipan
65	Cenozoic	Tertiary	Gulf Coast Carrizo-Wilcox Hueco and Mesilla Bolsons Ogallala Queen City and Sparta Igneous Yegua and Jackson
141	Mesozoic	Cretaceous	Woodbine Edwards-Trinity Plaueau Edwards-Trinity (High Plains) Trinity Group Nacatoch Blossom Rita Blanca
202	Mesozoic	Jurassic	Rita Blanca
250	Mesozoic	Triassic	Dockum
290	Paleozoic	Permian	Blaine Bone Spring-Victorio Peak Capitan Reef Complex Rustler Lipan Whitehorse-Artesia
323	Paleozoic	Pennsylvanian	Marble Falls Marathon
363	Paleozoic	Mississippian	Marathon
409	Paleozoic	Devonian	Marathon
439	Paleozoic	Silurian	Marathon
510	Paleozoic	Ordovician	Ellenburger-San Saba Marathon
544	Paleozoic	Cambrian	Ellenburger-San Saba Hickory
	Precambrian		

APPENDIX B

TWDB REVIEW COMMENTS AND RESPONSES

The following items called for in the Scope of Work were either not found or completely addressed:

1. Costing component addressing different treatment approaches, their respective capital costs, and O&M costs

   Response: This report summarizes the same treatment costing components that were addressed in the report by HDR and others (2000), which meets the requirements in the scope of work.

2. Treatment approaches considering production volumes, pre-treatment requirements and disposal of brine.

   Response: This report summarizes the same treatment approaches that were addressed in the report by HDR and others (2000), which meets the requirements in the scope of work.

3. The information provided on the aquifer characteristics of various brackish water reservoirs may not have been fully met as required in the "Scope of Work". Aquifer characteristics based on existing data or best professional judgement should be included in the discussion of each aquifer.

   Response: Concur. Aquifer characteristics, or estimates of aquifer characteristics based on best professional judgement, have been added to each aquifer section.

Other Comments:

4. Reviewers could not locate a mention of the 5,000 below ground level limitation on brackish groundwater considered in this study in the general discussion sections of the report.

   Response: Concur. This statement has been removed from the text.

5. The second paragraph of page 8 discusses several factors that may facilitate or "force" the use of brackish groundwater. The paragraph should be re-phrased to indicate that several factors may "guide" the use of brackish groundwater.

   Response: Concur. The text has been revised to remove "force" reference.

6. The third paragraph of page 12 mentions the Whitehorse water-bearing unit. Some reference to the lithology of this aquifer should be included.

   Response: Concur. The text has been revised to include a reference of the lithology of the Whitehorse aquifer.

7. The discussion of geophysical log analysis in the second paragraph of page 14 needs clarification.

   Response: Concur. The text has been revised per discussion between Bill Klemt of LBG-Guyton and Randy Williams of the TWDB.

8. The first paragraph of page 15 should state that the report is intended to support regional water supply planning decision-making.

   Response: Concur. The text has been revised.

9. The second paragraph of page 15 describes brackish groundwater as being considered unusable. The paragraph should state that brackish groundwater was previously considered unusable.

   Response: Concur. The text has been revised.

10. The first paragraph of page 19 discusses the availability of brackish groundwater. This discussion should be expanded.

    Response: Concur. The text has been expanded.

11. The second paragraph of page 19 discusses the well field productivity assesment made for this report. This discussion should be clarified and include the range of values considered for the "low, medium and high" designations.

    Response: Concur. The text has been revised to make this discussion more concise. In addition, range of values for "low, medium, and high" are included in the table.