Jon S. Albright

Tyler A. Davidson, P.E.

David W. Sloan, P.E., BCEE

San Angelo Groundwater Evaluation

Phase I Report

Initial Feasibility Assessment

January 10, 2006

Prepared by:

Freese and Nichols, Inc.
4055 International Plaza
Suite 200
Fort Worth, TX 76109
817/735-7300

LBG-Guyton Associates
1101 S. Capital of Texas Hwy.
Suite B-220
Austin, TX 78746
512/327-9640

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SAN ANGELO GROUNDWATER EVALUATION
PHASE I REPORT
INITIAL FEASIBILITY ASSESSMENT

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Executive Summary

The 2005 *Region F Initially Prepared Plan*[1] identified a potential water supply shortage for the City of San Angelo of almost 4,000 acre-feet per year in the year 2010, increasing to over 9,000 acre-feet per year by 2060. This report is an evaluation of four potential sources of water identified by the City of San Angelo to meet future needs:

1) Brackish groundwater from formations west of the City of San Angelo,
2) Brackish groundwater from formations north of the City of San Angelo,
3) Fresh water from the Edwards-Trinity aquifer south of the city, and
4) Fresh water from the Hovey Trough in southwestern Pecos County.

Of these four options, the Whitehorse aquifer, a brackish groundwater source located just west of the City of San Angelo, has been identified as the most likely potential source of water for the city (Option 1).

An evaluation of potential treatment options for brackish water from the Whitehorse aquifer indicate that reverse osmosis is the most feasible treatment option. Concentrate reject from the treatment process could be disposed of using either dedicated injection wells or in conjunction with nearby oil field operations. This report includes a conceptual delivery and treatment design for the project with an initial capacity of five million gallons per day (MGD) with the potential to expand to 10 MGD. Table ES-1 is a summary of the probable costs for this project.

Table ES-1: Costs for Desalinated Water from the Whitehorse Aquifer

	5 MGD	**10 MGD**
Supply from Strategy	5,600 acre-feet per year	11,200 acre-feet per year
Total Capital Costs (2005 Prices)	$ 28,921,000	$ 48,008,000
Annual Costs	$ 1,535,000	$ 2,931,000
Unit costs	$ 724 per acre-foot	$ 635 per acre-foot
	$ 2.22 per 1,000 gallons	$ 1.95 per 1,000 gallons

Although existing data indicate that Whitehorse aquifer will be an attractive potential water supply source for the city, currently there are no water supply wells completed in the study area. An exploration program will be required to verify the water quality and productivity of the aquifer.

1 Introduction

The city of San Angelo is located in Tom Green County in West Texas. As one of the largest cities in the area, it is a major center of employment, trade and cultural activities. The city receives water from six sources: Lake Nasworthy, Twin Buttes Reservoir, the Concho River, O.C. Fisher Reservoir, Ivie Reservoir, and Spence Reservoir. The city owns the rights for water from Lake Nasworthy, Twin Buttes Reservoir and the Concho River. The rights for O.C. Fisher are owned by the Upper Colorado River Authority (UCRA). Ivie and Spence Reservoirs are owned and operated by the Colorado River Municipal Water District (CRMWD). Table 1-1 is a summary of water rights data for the city's surface water sources. The city also owns an undeveloped groundwater well field in the Hickory aquifer in McCulloch County.

Since 1998, the city has been hard-hit by a region-wide drought. Twin Buttes Reservoir and O.C. Fisher Reservoir have been at 10 percent capacity or less. Downstream senior irrigation water right holders on the Concho River made priority calls on Twin Buttes Reservoir, obligating the city to pass inflows. During the drought, the city obtained most of its water from Ivie Reservoir. Through water conservation and drought management the city avoided actual shortage during the drought. Although conditions have improved somewhat in 2005, the city's water supplies remain vulnerable to continued drought conditions.

As a result of the drought, the city convened a citizens group to guide water supply activities and studies. In February of 2004, the San Angelo City Council, the Citizen's Water Advisory Board, and the City Staff published the results of this process in the report *San Angelo Water Preparing for the Next 50 Years*[2]. In this report five preferred strategies were identified:

- Develop and communicate public and private conservation and drought management programs;
- Develop reclamation, reuse and water storage alternatives;
- Protect and enhance existing surface water resources;

Table 1-1: Summary of Surface Water Rights for San Angelo Water Sources

Source	Owner	Water Right Holder	Water Right Number	Priority Date	Permitted Storage (Ac-Ft)	Permitted Diversion (Ac-Ft/Yr)	Use Type	Comments
Twin Buttes Reservoir	Bureau of Reclamation	City of San Angelo	CA 1318	5/6/1959	170,000	4,000	Mun	Plus the 25,000 authorized in CA 1319
						25,000	Irr	
						29,000	*Total*	
Lake Nasworthy	City of San Angelo	City of San Angelo	CA 1319	3/11/1929	12,500	17,000	Mun	
						7,000	Ind	
						1,000	Irr	
						25,000	*Total*	
O.C. Fisher Reservoir	Army Corps of Engineers	UCRA	CA 1190	5/27/1949	80,400	80,400	Mun, Ind, Min, Rec	
Concho River Rights	City of San Angelo	City of San Angelo	CA 1191	10/13/1931	150		Rec	
			CA 1298	7/29/1914	50	128	Mun, Irr	
				10/8/1931	8	124	Mun, Irr	
			CA 1323	4/1/1914	1,157		Rec	Metcalf Dam
			CA 1325	5/16/1914	300	1,534	Mun, Ind	Lone Wolf Reservoir
			CA 1326	3/11/1953	370		Mun	Bell Street Reservoir
			CA 1333	1/3/1921		184	Irr	
			CA 1337	1/3/1921	130	135	Irr	
			CA 1357	10/31/1916	75	200	Mun, Irr	
				12/31/1918		136	Mun, Irr	
			CA 1401	12/8/1916	316	5,000	Mun	
					2,556	*7,441*	*Total*	
			Total Local Water Rights		*265,456*	*141,841*		

Table 1-1: Summary of Water Rights for San Angelo Water Sources (continued)

Source	Owner	Water Right Holder	Water Right Number	Priority Date	Permitted Storage (Ac-Ft)	Permitted Diversion (Ac-Ft/Yr)	Use Type	Comments
E.V. Spence Reservoir	CRMWD	CRMWD	CA 1008	8/17/1964	488,760	38,573	Mun	3,000 ac-ft/yr or 6% of safe yield contracted to San Angelo
						2,000	Ind	May also be diverted into Barber, Red Draw or Mitchell Co. Res.
						1,000	Min	May also be diverted into Barber, Red Draw or Mitchell Co. Res.
						41,573	*Total*	
O.H. Ivie Reservoir	CRMWD	CRMWD	A 3866	2/21/1978	554,340	103,000	Mun	15,000 ac-ft/yr or 16.54% of safe yield
			P 3676			10,000	Ind	contracted to San Angelo
						113,000	*Total*	
				CRMWD Total	*1,043,100*	*154,573*		Currently 18,000 ac-ft/yr contracted to San Angelo

Notes:

CA Certificate of Adjudication
P Permit
A Application

Mun Municipal
Ind Industrial
Irr Irrigation
Min Mining
Rec Recreation

- Expand cooperative efforts and agreements to increase water availability for both urban and rural areas; and
- Identify and develop fresh and brackish groundwater alternatives.

This report evaluates four of the fresh and brackish groundwater alternatives identified by the Advisory Board:

- Brackish groundwater from formations west of the City of San Angelo,
- Brackish groundwater from formations north of the City of San Angelo,
- Fresh water from the Edwards-Trinity aquifer south of the city, and
- Fresh water from the Hovey Trough in southwestern Pecos County.

1.1 Comparison of Existing Supplies to Projected Demands

Table 1-2 compares the City of San Angelo's current supplies to projected demands. These data are from the 2005 *Region F Initially Prepared Plan*[1]. The supplies for the reservoirs and the Concho River water rights are based on the Texas Commission on Environmental Quality (TCEQ) Colorado Water Availability Model (Colorado WAM)[3]. In this model, all of San Angelo's local reservoir supplies and Spence Reservoir have little or no firm yield. Ivie Reservoir is the only significant source of water with a reliable yield. The model shows a small reliable supply from three of the city's run-of-the-river permits. These results are due to the assumptions used by TCEQ in the Colorado WAM model and do not necessarily reflect the amount of water available from these reservoirs. Detailed information regarding these results may be found in the *Region F Initially Prepared Plan.*

In order to make a more realistic assessment of water supplies, Region F evaluated supplies for the San Angelo reservoirs assuming that major downstream senior water rights belonging to LCRA, the City of Corpus Christi and the City of Austin would not make priority calls on these reservoirs. (Other, smaller senior water rights were assumed to assert their right to make priority calls from these reservoirs.) The additional yield with this assumption is labeled as "Subordination Supply" in Table 1-2. Using these supplies, the City of San Angelo currently has a little more than 23,400 acre-feet of available supply in 2010, decreasing to just under 20,700 acre-feet by 2060. More

Table 1-2: Comparison of Supply and Demand for the City of San Angelo
(Values in Acre-Feet per Year) [a]

Supplies	2010	2020	2030	2040	2050	2060
Twin Buttes/Nasworthy [b]	0	0	0	0	0	0
O.C. Fisher [b]	0	0	0	0	0	0
Concho River [b]	642	642	642	642	642	642
Subordination supply [c]	11,791	11,472	11,153	10,835	10,516	10,196
Spence Contract [d]	0	0	0	0	0	0
Ivie Contract [e]	10,974	10,751	10,528	10,304	10,081	9,858
Total	*23,407*	*22,865*	*22,323*	*21,781*	*21,239*	*20,696*
Demand	**2010**	**2020**	**2030**	**2040**	**2050**	**2060**
City of San Angelo	20,800	21,418	21,734	21,744	21,907	21,969
City of Miles	100	100	100	100	100	100
Municipal Sales	250	250	250	250	250	250
Manufacturing	2,226	2,498	2,737	2,971	3,175	3,425
Steam-Electric	543	777	909	1,021	1,021	1,021
Irrigation [f]	3,480	3,377	3,273	3,170	3,067	2,963
Total	*27,399*	*28,420*	*29,003*	*29,256*	*29,520*	*29,728*
Surplus (Need)	*(3,992)*	*(5,555)*	*(6,680)*	*(7,475)*	*(8,281)*	*(9,032)*

a Data are from the 2005 *Region F Initially Prepared Plan*
b Supply from the Colorado WAM.
c Supply assuming that downstream senior water rights belonging to LCRA, the City of Austin, and the City of Corpus Christi do not make priority calls.
d Supplies from Spence Reservoir are currently not available to the city because infrastructure to supply the water to the city is not functional.
e The Region F water plan assumes that CRMWD invokes provisions in the Ivie water supply contract to limit supplies from Ivie Reservoir to 16.54 percent of the safe yield of the reservoir. Currently, the contract amount from Ivie Reservoir is 15,000 acre-feet per year.
f Demand set to amount of yield from Twin Buttes/Nasworthy needed to make 18,000 ac-ft/yr interruptible supply available for irrigation.

detailed information regarding the water supply analysis may be found in the *Region F Initially Prepared Plan.*

The supplies from CRMWD reservoirs (Spence and Ivie) have been adjusted to reflect yields determined with the Colorado WAM. The city's contracts with CRMWD are currently set at 3,000 acre-feet per year from Spence Reservoir and 15,000 acre-feet per year from Ivie Reservoir. These contracts also specify that, at the option of CRMWD, the contracted amount from these reservoirs can be reduced to 6 percent of the safe yield of Spence Reservoir and 16.54 percent of the safe yield of Ivie Reservoir. The Region F plan assumes that CRMWD will reduce available supplies to San Angelo based on the Region F safe yield of each source. Also, the city's pipeline from Spence Reservoir is not usable at this time and requires extensive rehabilitation. Therefore Region F considers supplies from Spence Reservoir to be unavailable until the pipeline has been repaired.

The Region F demands in Table 1-2 are for a dry year without implementation of water use restrictions or other drought management measures. During normal to wet years, demands will probably be somewhat less. Region F assumes that the City of San Angelo will supply approximately 250 acre-feet per year to connections outside of the city, all of the manufacturing water demand in Tom Green County, and up to 1,021 acre-feet of raw water for steam electric power generation. The city also supplies treated O.C. Fisher water to the City of Miles through an agreement with UCRA. Irrigation supplies from the Twin Buttes Reservoir/Lake Nasworthy system are supplied on an interruptible basis. During an extended drought supplies from this source may not be available. Irrigation demands from Twin Buttes Reservoir and Lake Nasworthy are set to the amount of the yield of the Twin Buttes/Nasworthy system needed to generate 18,000 acre-feet per year of interruptible yield.

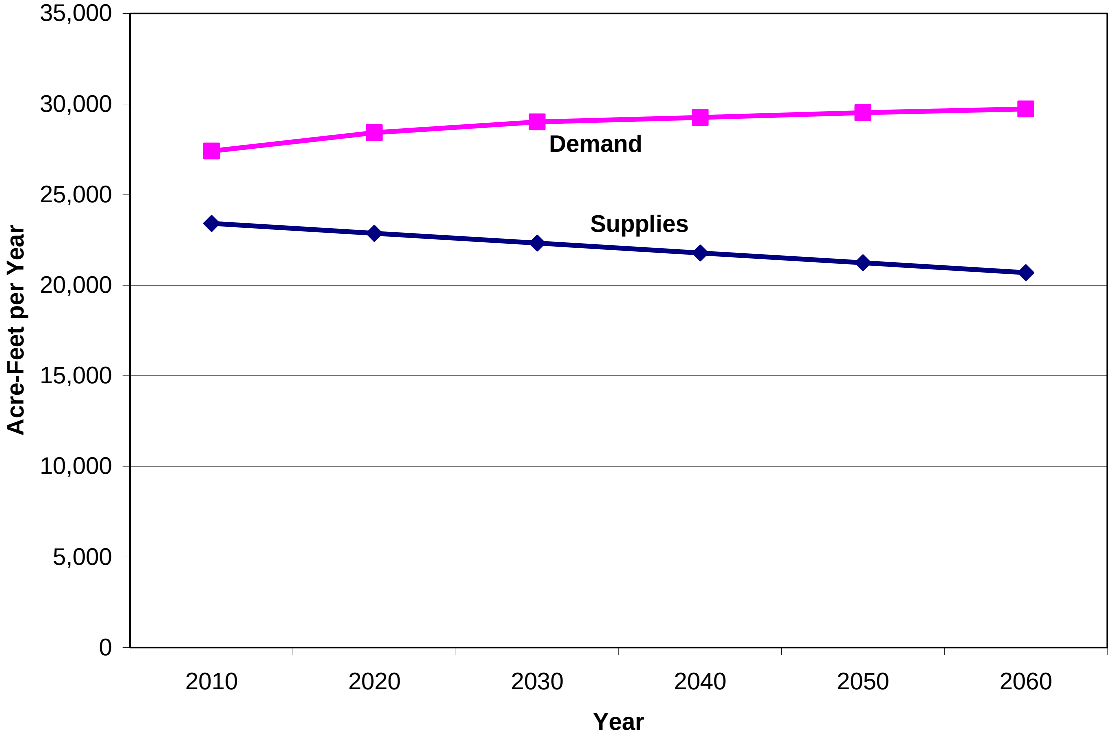
Using these supplies and demands, the City of San Angelo could experience supply needs of almost 4,000 acre-feet per year by 2010. By 2060, the supply needs increase to over 9,000 acre-feet per year. The overall comparison of supply and demand is illustrated in Figure 1-1.

1.2 Scope of Services

The scope of services for this project calls for development of a facility plan for groundwater supplies from one or more of the following options:

- Brackish groundwater from Triassic and Permian formations west of the City of San Angelo in Tom Green, Irion, and/or Reagan Counties;
- Brackish groundwater from Triassic and Permian formations north of the City of San Angelo in Coke County;
- Fresh groundwater from the Edwards-Trinity aquifer south of the city in Crockett and Sutton Counties; and
- Fresh groundwater from the Hovey Trough in southwestern Pecos County.

Figure 1-1: Comparison of Supply and Demand for the City of San Angelo



Phase I of this project, covered by this report, included the following tasks:

BRACKISH GROUNDWATER ASSESSMENT

A. Hydrogeological Evaluations

1. Identify specific supply areas for further investigation.
2. Identify other formations in the vicinity suitable for deep well injection. Identify other potential methods for disposal.
3. Collect existing information on water quality, formation characteristics and other information for both supply and disposal formations. Identify wells that penetrate these formations. Collect relevant information on these wells if available.
4. Identify up to five existing wells (if available) suitable for testing. Perform pump tests and comprehensive water quality analyses on these wells.
5. Based on above data, select specific areas suitable for well field development. Identify gaps in data for each location and develop a plan for further investigation.

B. Regulatory Assessment

Identify potential permitting, regulatory and environmental issues associated with source development, treatment, distribution and, where applicable, disposal of brine reject.

C. Conceptual Design

Develop a conceptual design for brackish desalination, including the following:
1. Approximate location of facilities and potential customers to be served
2. Treatment facilities
3. Well field(s)
4. Storage, pumping and pipeline facilities
5. Opinion of probable cost (capital and operational)

FRESH GROUNDWATER SOURCES

Evaluations of the two freshwater sources were developed as part of the *Region F Initially Prepared Plan* and are included in this report for comparison purposes.

Phase II of this study will include implementation of the investigation plan developed in Task A5. If the investigation shows that the identified brackish groundwater sources are cost-effective sources of water for San Angelo, a detailed Facilities Planning Report will be developed.

Funding for this project was provided by the Upper Colorado River Authority, the City of San Angelo, the Texas Water Development Board, and the Region F Water Planning Group.

2 Potential Groundwater Sources

The City of San Angelo has identified five potential groundwater sources for further investigation:

- Brackish water from Triassic and Permian aquifers west of San Angelo;
- Brackish water from Triassic and Permian aquifers north of San Angelo;
- The Edwards-Trinity (Plateau) aquifer in Crockett, Schleicher and Sutton Counties;
- The Hovey Trough in Pecos County; and
- The Hickory aquifer in McCulloch, Concho and Menard Counties.

Supplies from the Hickory aquifer are being evaluated by others. This study focuses on the four other groundwater supply options.

2.1 Edwards-Trinity (Plateau) Aquifer

Extending from the Hill Country of Central Texas to the Trans-Pecos region of West Texas, the Edwards-Trinity (Plateau) aquifer is comprised of water-bearing portions of the Edwards Formation and underlying formations of the Trinity Group, including the Glen Rose Limestone and Antlers Sand (see Figure 2-1). Regionally, this aquifer is categorized by the TWDB as one aquifer; however, the Edwards and Trinity components are not everywhere hydrologically connected and can be considered as separate aquifers. The Trinity includes the Antlers Sand in the northwest part of the region, and the Glen Rose Limestone in the southeast part.

Water in the Edwards-Trinity (Plateau) aquifer generally flows in a south-southeasterly direction, but may vary locally. Reported well yields commonly range from less than 50 gallons per minute (gpm) from the thinnest saturated section to 1,000 gpm in locations where wells are completed in jointed or cavernous limestone.

Of approximately 4,000 water sample analyses in the TWDB water quality database, 39 percent have total dissolved solids (TDS) concentrations over the 1,000 mg/l standard for drinking water. Average TDS of aquifer samples is approximately 800 mg/l. The chemical quality water in the Edwards formation is generally better than that in the underlying Trinity formation.

Freese and Nichols
4055 International Plaza, Suite 200
Fort Worth, TX 76109 - 4895
Phone - (817) 735 - 7300

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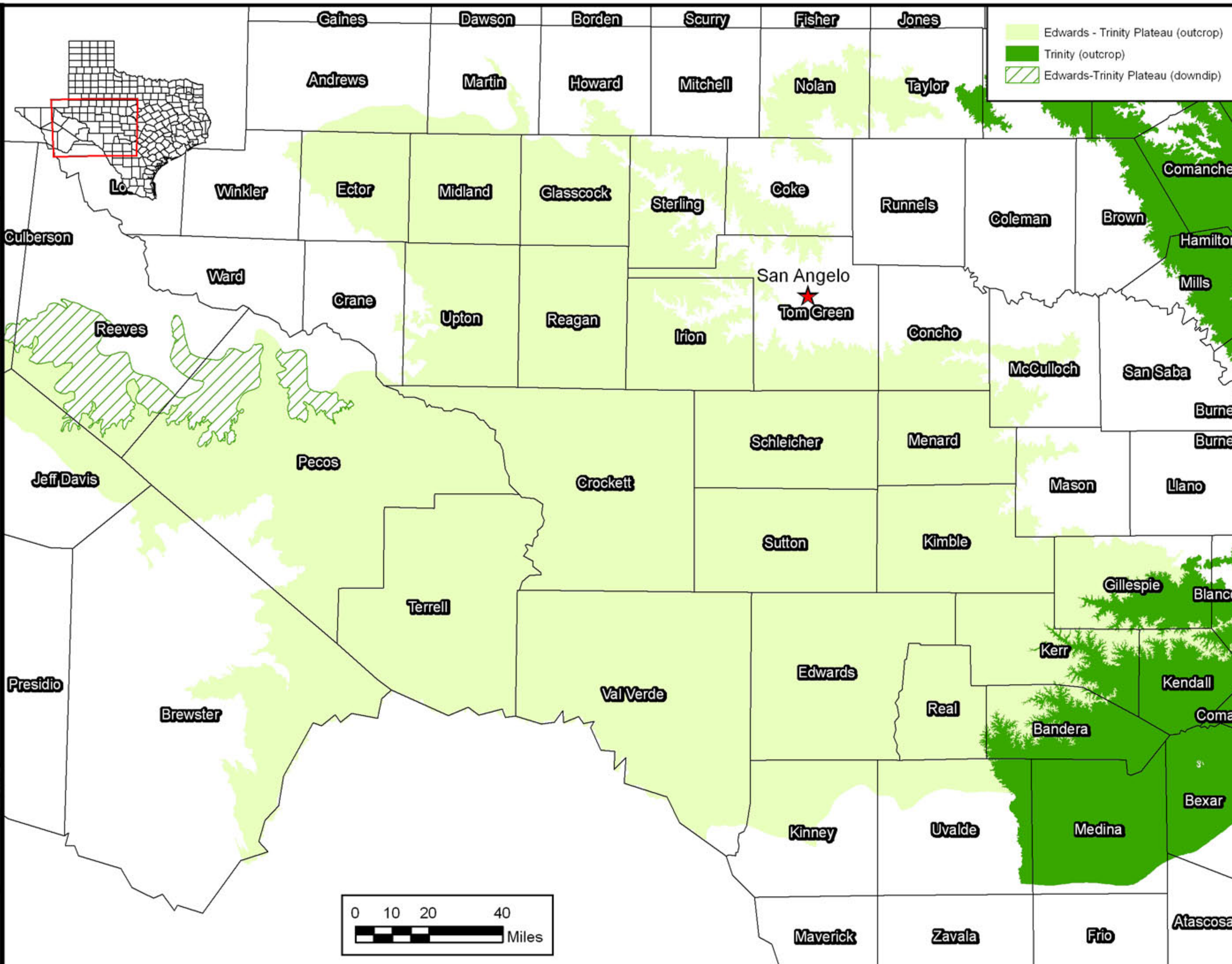
Edwards-Trinity (Plateau) Aquifer Location Map

FN JOB NO URA04298
FILE AquiferLocationMap.mxd
DATE July 13, 2005
SCALE 1:2,000,000
DESIGNED BME
DRAFTED BME

FIGURE 2-1



According to the *Region F Initially Prepared Plan*[1], over 62,000 acre-feet of water per year are available from the Edwards-Trinity in Crockett, Schleicher and Sutton Counties. Most of the fresh water is contained in caverns or fractures in the Edwards limestone. This type of porosity tends to be highly localized, and areas with high porosity and production are not well documented. An exploration program would be required to find suitable areas for municipal development.

In 1985 the City of San Angelo investigated the possibility of developing a water supply from the Edwards-Trinity (Plateau) aquifer in northern Schleicher County[4]. This study concluded the following:

- Water quality of the Edwards limestones was of good quality. The water quality of the Trinity sands was somewhat poorer in quality.
- Water production from the Edwards limestones appears to be from cavernous porosity and could provide sufficient water for municipal supply. The Trinity sand is poorly developed, contains a high percentage of clay and is less attractive for large-scale water development.
- Drought conditions from 1962 to 1967 caused water levels in the Edwards to drop by 15 to 20 feet.
- Models of production from a proposed well field near Hulldale had a significant impact on the Anson springs. These springs provide much of the base flow of the South Concho River, which flows into Twin Buttes Reservoir.

The 1985 study proposed construction of a 30-mile 30-inch pipeline with a capacity of 15 mgd and development of a well field with 10 wells. Because the 1985 study indicated that groundwater development from the Edwards-Trinity aquifer may significantly reduce springflow, a detailed study of the potential impacts of groundwater development should be conducted if this source of water is pursued by the city. If necessary, pumping limits in addition to those already imposed by the local groundwater conservation districts may be necessary to protect the environment.

Table 2-1 is a cost estimate from the 2005 Region F plan based on the 1985 study, updated to year 2002 costs.

Table 2-1: Costs for Water from Edwards-Trinity (Plateau) Aquifer

Supply from Strategy	12,000 acre-feet per year
Total Capital Costs (2002 Prices)	$ 31,365,000
Annual Costs	$ 5,620,000
Unit costs (before amortization)	$ 468 per acre-foot
	$ 1.44 per 1,000 gallons
Unit Costs (after amortization)	$ 240 per acre-foot
	$ 0.74 per 1,000 gallons

Data are from the Region F *Initially Prepared Plan*

Pumping limits and well spacing rules adopted by the Schleicher and Sutton County Groundwater Conservation Districts discourage the large-scale development of groundwater from the Edwards-Trinity. Rule changes may be necessary for development of water by the City of San Angelo from these counties. However, there is strong local opposition to the export of groundwater from Sutton and Schleicher Counties, and this represents a significant barrier to its development as a water resource for San Angelo. It is doubtful these political obstacles can be overcome within the foreseeable future.

2.2 Hovey Trough

A group of landowners in southwestern Pecos County is marketing groundwater from an area known as the Hovey Trough. The Hovey Trough is an area of alluvial gravels at the base of the Glass Mountains southwest of Fort Stockton, approximately 175 miles west of San Angelo (see Figure 2-2). The gravel beds are over 30 miles long and 10 miles wide, encompassing an area of approximately 10,000 acres. Recharge to the area is provided by runoff from the Glass, Davis and Barilla Mountains[5]. The gravel beds have not been included in a named aquifer by the Texas Water Development Board (TWDB), although the Hovey Trough appears to be hydraulically connected to the Edwards-Trinity (Plateau) aquifer (see Figure 2-3).

The sustainable quantity of water from Southwestern Pecos County has not been established. Preliminary estimates indicate that 50,000 to 100,000 acre-feet per year could be provided from this source. Additional studies will be needed to verify these quantities. Water quality is expected to be good, with total dissolved solids concentrations less than 500 mg/L. Water quality down-dip in the Edwards-Trinity tends to be more saline, averaging approximately 1,000 mg/L TDS[5].

Freese and Nichols
4055 International Plaza, Suite 200
Fort Worth, TX 76109 - 4895
Phone - (817) 735 - 7300

Hovey Trough Location Map

San Angelo Groundwater Evaluation

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URA04298	CloseUp.mxd	July 13, 2005	1:1,320,000	BME	BME

FIGURE 2-2

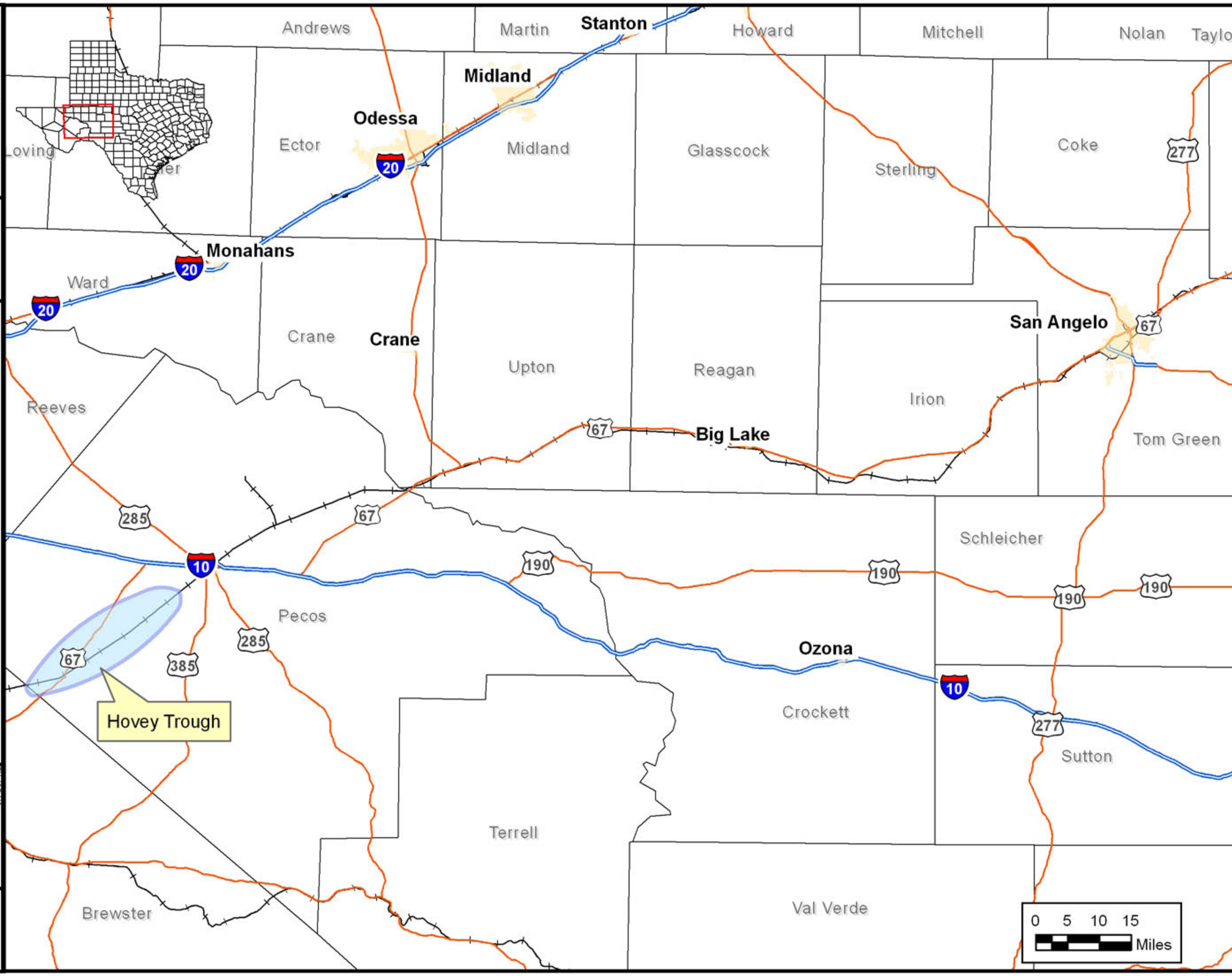
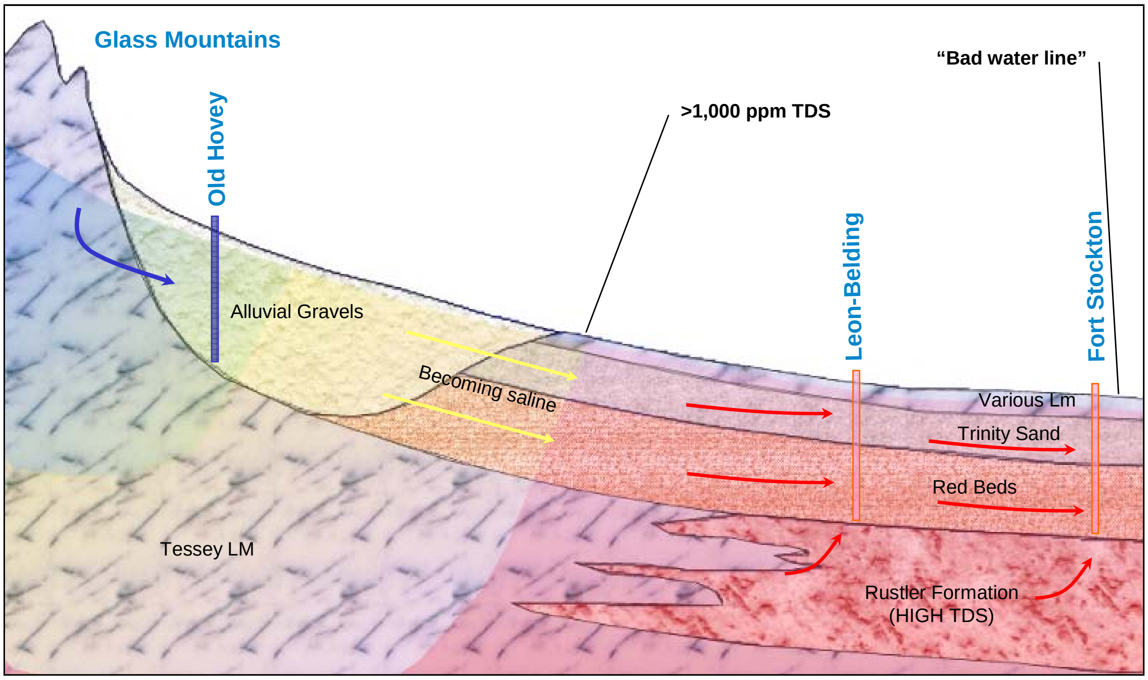


Figure 2-3: Hovey Trough Cross Section



Source: Layne Water Development Corporation

The estimated supplies from this source exceed the needs of the City of San Angelo. The Region F *Initially Prepared Plan* assumes that the City of San Angelo could take up to 12,000 acre-feet per year from this source. Table 2-2 shows the costs as developed by Region F. Because of the long distance from the source, the cost-effectiveness of this project is highly dependent upon the amount of water produced and used from this source. Participation by other entities would be necessary for this project to be cost-effective.

Information provided by the sponsors of this project indicates possible impacts on flow in the Pecos River from development of this strategy[5], which should be investigated if this strategy is pursued. If linkage between groundwater development and flows in the Pecos River is established, the local groundwater conservation district may seek to impose pumping limits.

Table 2-2: Costs for Water from the Hovey Trough

Supply from Strategy	12,000 acre-feet per year
Total Capital Costs (2002 Prices)	$ 194,052,000
Annual Costs	$ 22,401,000
Unit costs (before amortization)	$ 1,867 per acre-foot
	$ 5.73 per 1,000 gallons
Unit Costs (after amortization)	$ 457 per acre-foot
	$ 1.40 per 1,000 gallons

Data are from the Region F *Initially Prepared Plan*

According to information provided by the developers of this project, the supply in the immediate area is primarily used for cattle ranching and development of the project will have minimal impact on existing uses. However, it is possible that large-scale production from this source could reduce irrigation supplies in the Belding Farms area. Additional studies may be needed to quantify this impact.

2.3 Triassic and Permian Aquifers

2.3.1 Aquifer Evaluation

With advanced treatment, brackish water aquifers represent a promising source of water supply for the City of San Angelo. (Treatment options are discussed in Chapter 3 of this report.) This study focuses on Triassic (Dockum) and Permian formations north and west of the city of San Angelo in Tom Green, Irion and Coke Counties. Figure 2-4 is a conceptual cross-section of these formations. The potential sources of brackish groundwater include the Clear Fork Group, the Pease River, the Blaine Formation and the Whitehorse Group (see Figure 2-5). Appendix B contains a detailed evaluation of these formations as potential brackish water sources for the City of San Angelo. The Whitehorse Group has been identified as the most promising source of brackish water for the City of San Angelo. Areas north of San Angelo are less promising because of lack of promising sand formations and concerns about concentration of calcium sulfate, which can significantly lower the recovery rates from the desalination process.

Figure 2-4: West to East Conceptual Geologic Cross Section

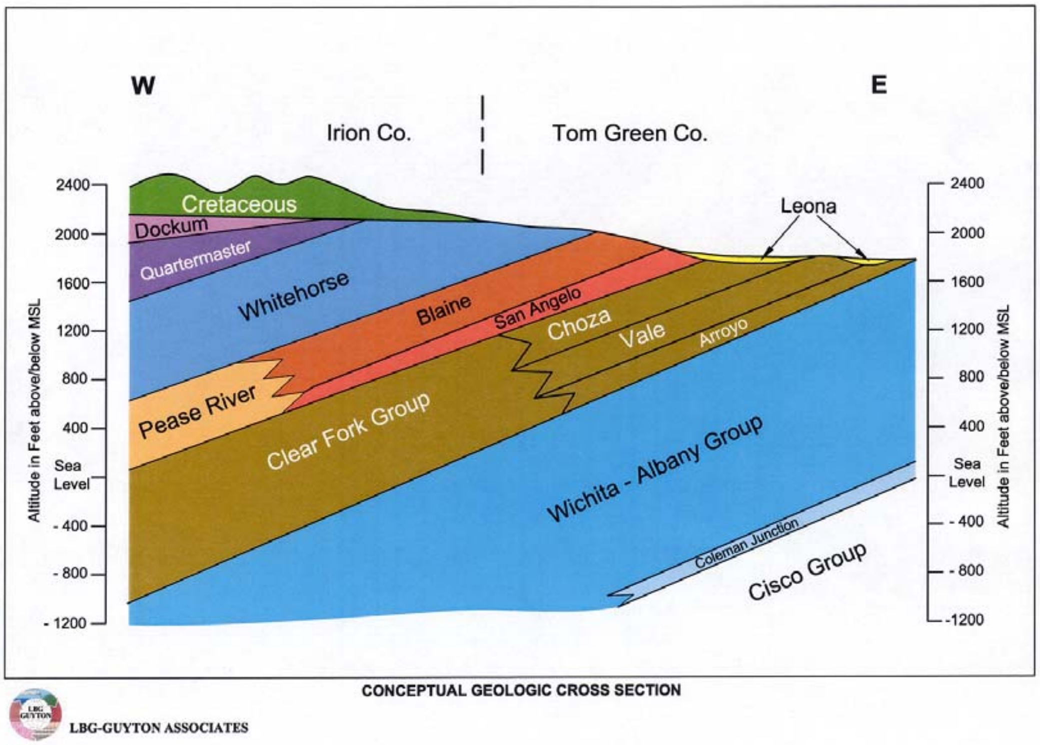
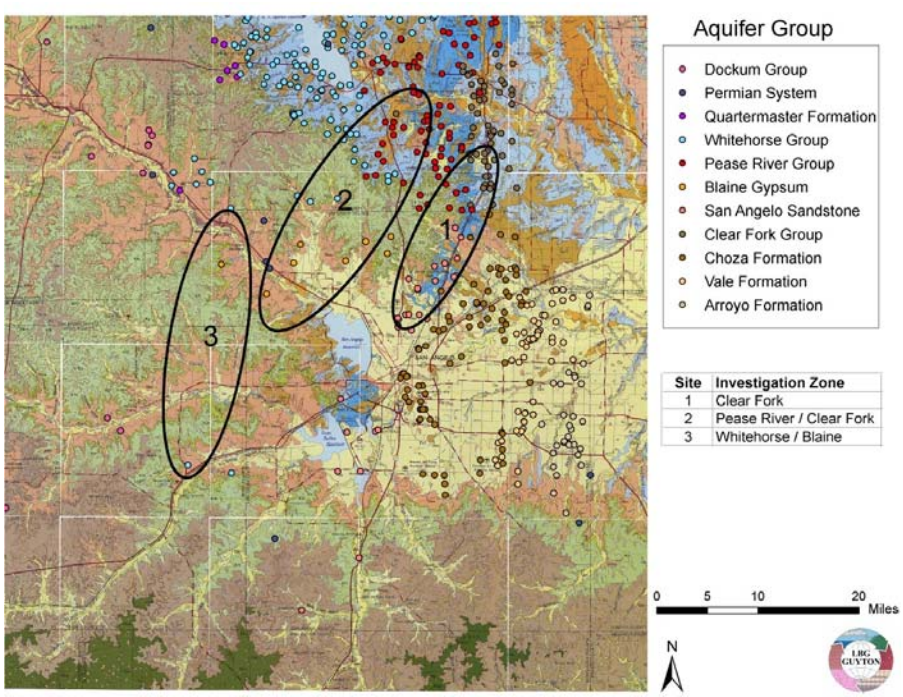


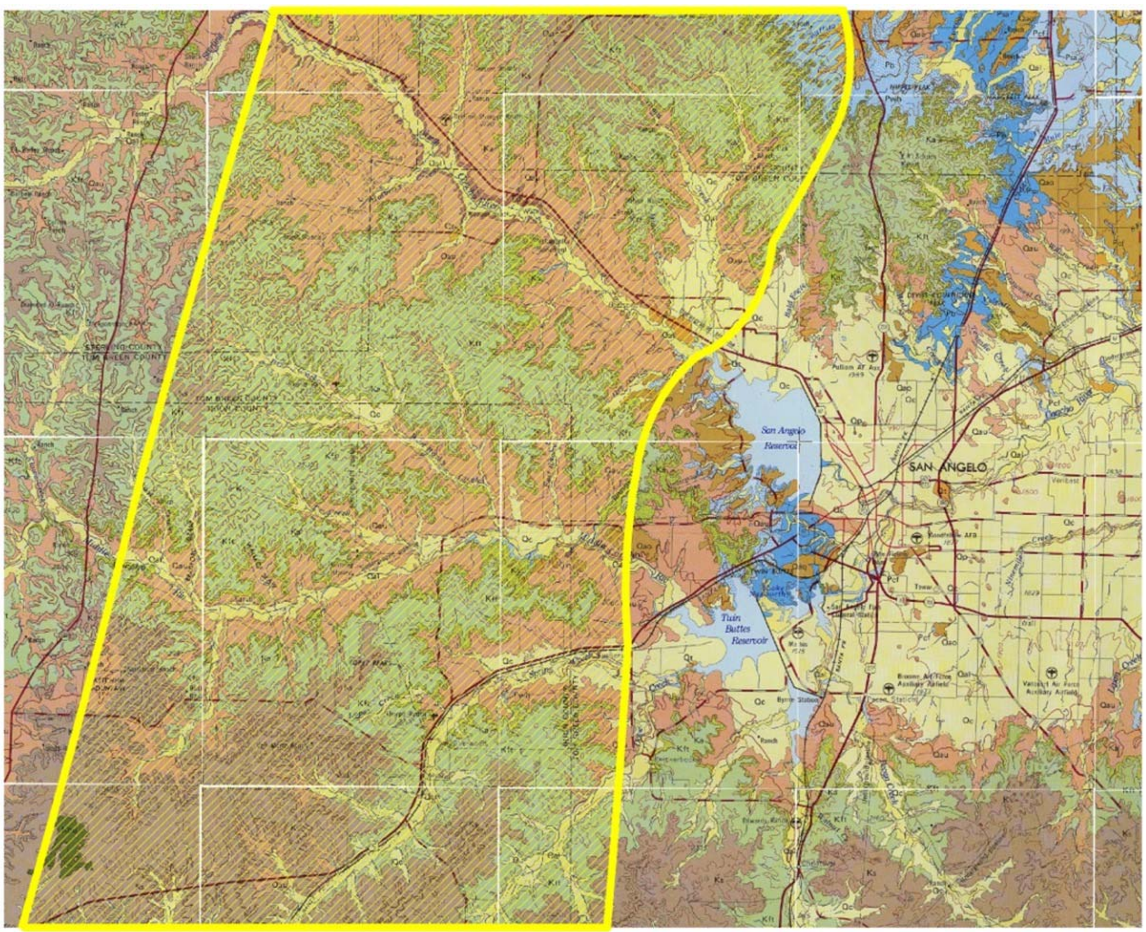
Figure 2-5: Brackish Source Investigation Areas with Wells



2.3.2 Whitehorse Group

The Whitehorse Group consists of fine-grained red sand, dolomite, and gypsum beds. The Whitehorse crops out in a few small isolated locations in eastern Irion County and in a larger area surrounding and probably underlying Spence Reservoir. A few wells in Irion County produce from the Whitehorse, while numerous moderately shallow wells are located on the Whitehorse outcrop surrounding Spence Reservoir. In the vicinity of San Angelo, the aquifer has an average thickness of 200 feet with an average porosity of 15 percent. It is estimated that in the 1,700 square miles of the aquifer in the San Angelo area, this aquifer contains 30 million acre-feet of water (see Figure 2-6).

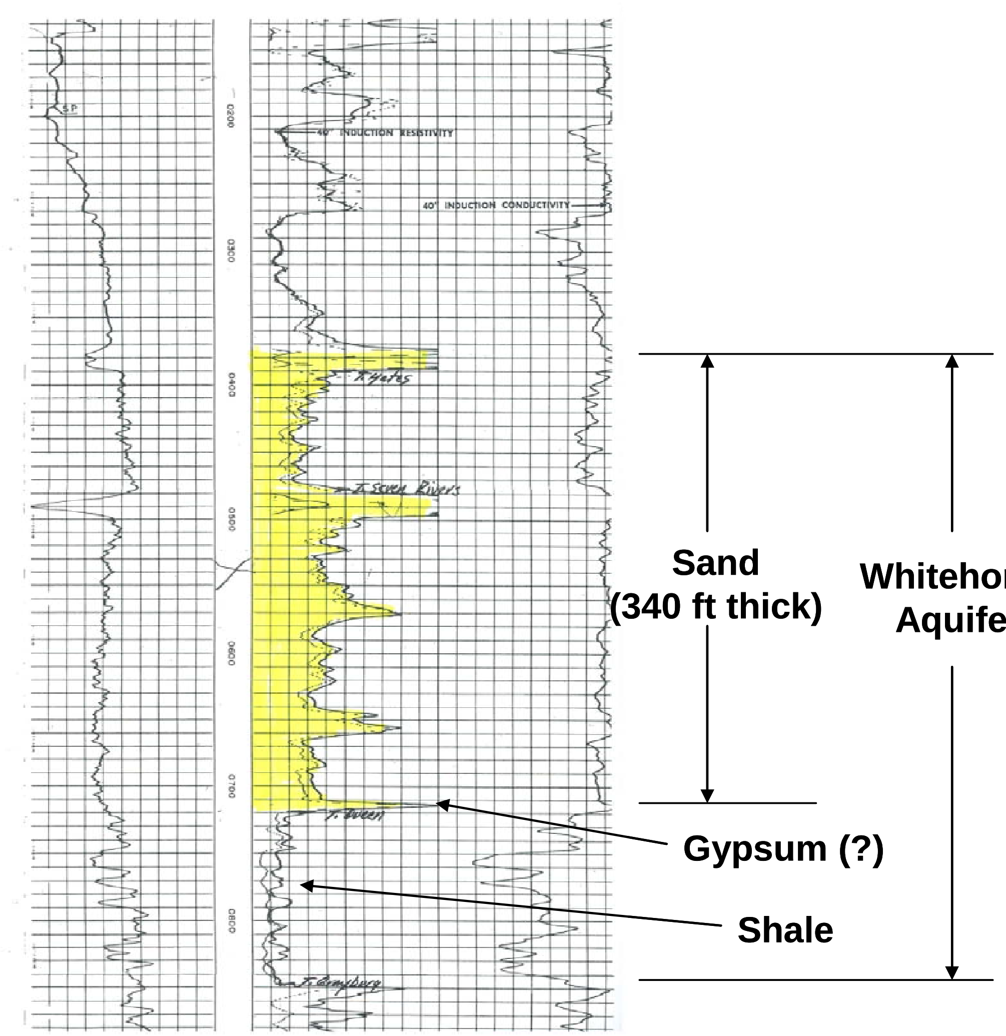
Figure 2-6: Approximate Whitehorse Aquifer Extent in the San Angelo Area



Water quality from the Whitehorse aquifer varies greatly with generally moderately high concentrations of calcium, sulfate, and TDS. Fresh water may be encountered in the Whitehorse in recharge areas; however, water quality rapidly deteriorates in downdip portions of the aquifer.

In most of the existing water wells, yields are generally less than 200 gpm. The more prolific of the existing water wells are in areas that produce from fractures and cavities in the formation matrix. However, the geophysical logs from oil and gas wells that penetrate the Whitehorse show extensive sands throughout the area that appear to be promising potential sources of water (see Figure 2-7). None of the existing water wells penetrate these sands.

Figure 2-7: Example Geophysical Log in Whitehorse Aquifer Exploration Area



Although the Whitehorse aquifer appears to be a promising source of water, there are no existing water wells that produce from the sands identified in the preliminary investigation. To finish the evaluation of this source, an exploration program that involves drilling up to six test wells into the Whitehorse aquifer is proposed. These test wells will be used to evaluate the geology of the aquifer and gather water quality samples. Two of the most promising sites may be chosen for pump tests. A complete description of the exploration program may be found in Appendix C. If water quality and pump testing show that water from the Whitehorse aquifer will be cost-effective to treat, Phase II of this project, development of a Facility Planning Report, will be initiated.

2.4 Comparison of Alternatives and Recommendations

The three sources evaluated in this study (the Edwards-Trinity (Plateau) aquifer south of the city, the Hovey Trough in Pecos County, and brackish water from areas north or west of San Angelo) have been compared based on the following screening criteria:

- *Quantity and reliability*. Is the source sufficient to meet San Angelo's needs?
- *Availability.* Is the source available for use by the City of San Angelo? Are there any physical or institutional barriers to development of the source?
- *Potential impacts.* Are there potential impacts to the environment, other water users or third parties that need to be considered before developing the source? Could these impacts be a significant barrier to development of the source?
- *Cost.* What is the estimated cost of the source? Is this source a cost-effective alternative for San Angelo?

Edwards-Trinity (Plateau) Aquifer

Quantity and Reliability

Areas with sufficient porosity for municipal production are not well-known and the aquifer tends to be impacted by drought. An exploration program will be needed to verify quantity and reliability of water for municipal purposes.

Availability

Local groundwater districts' rules make large-scale development of the aquifer difficult. Strong local political opposition is likely to result in protracted legal challenges if the City of San Angelo elects to pursue this option.

Potential Impacts

Large-scale water development is likely to reduce streamflows, potentially impacting both the environment and surface water users, including the City of San Angelo.

Cost

At $240 per acre-foot, supplies from the Edwards-Trinity (Plateau) aquifer may be the most economical source of groundwater for the City of San Angelo.

Hovey Trough

Quantity and Reliability

Preliminary estimates indicate water from the Hovey Trough could provide a significant new source of supply for West Texas. However, additional studies will be needed to verify the sustainable supplies available from this source.

Availability

The Hovey Trough is more than 175 miles from San Angelo. The project would not be cost-effective for San Angelo unless other large water users such as CRMWD and/or the City of Midland participate in development of the project.

Potential Impacts

Potential impacts on other water users and flows in the Pecos River need to be evaluated.

Cost

Water from the Hovey Trough will probably not be economical for the City of San Angelo to develop alone. Other participants in the project could significantly reduce the cost.

Brackish Sources

Quantity and Reliability

Because of thick sand layers in the formation, brackish water from the Whitehorse aquifer appears to be a promising source of water for the City of San Angelo. No water wells penetrate the portion of the aquifer that has been identified in this study. An exploration program is needed to gain specific data necessary to quantify the treatability of the water and the productivity of the aquifer.

Availability

There is no current use from this source and no barriers to development have been identified.

Potential Impacts

No impacts have been identified.

Cost

Although the water requires advanced treatment to make it suitable for municipal use, preliminary cost estimates indicate that water from this source may be as cost-effective as fresh-water sources that are farther away.

Recommendations

Of the options evaluated in this study, brackish water from the Whitehorse aquifer appears to be the most promising alternative and the remainder of this report will focus on development of water from that source. Although the Edwards-Trinity (Plateau) aquifer is probably the most economical of the alternatives evaluated in this study, the institutional and potential environmental impacts of water development make this option less attractive than the brackish water alternative. Because of the distance from the city, the Hovey Trough is the least attractive of the sources evaluated in this study. However, participation by other entities may make this source viable in the future.

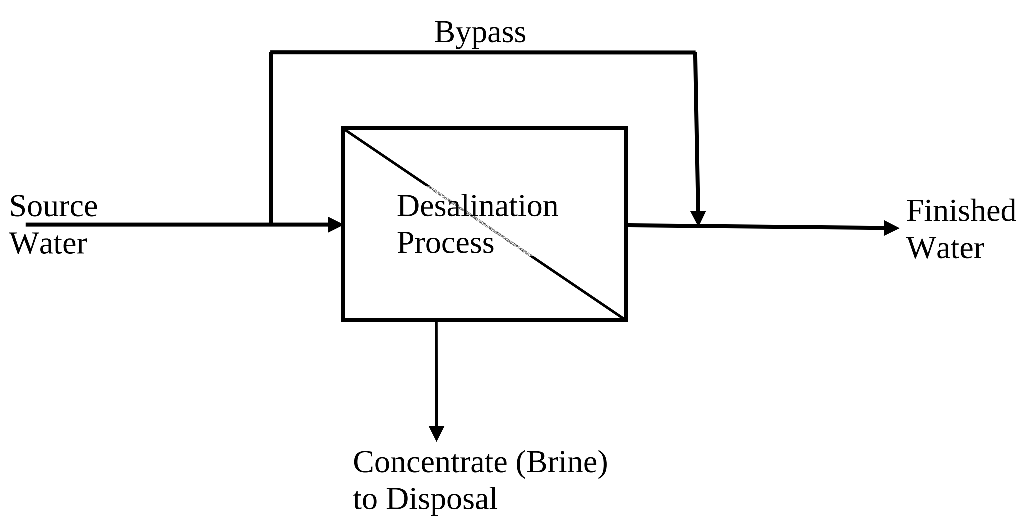
3 Desalination

Water desalination is the removal of salts and dissolved solids from saline water (brackish or seawater). In addition to the removal of minerals, some processes also remove biological and organic chemical compounds.

3.1 Desalination Methods

Most desalination processes are based on reverse osmosis, electrodialysis, ion exchange or thermal distillation technologies. These processes typically accomplish nearly complete removal of salts, and it is common to bypass a portion of the source water and blend it with the desalination product to economically achieve the desired salinity, as illustrated in Figure 3-1. The candidate processes are described in the following sections.

Figure 3-1: Typical Desalination Process Configuration

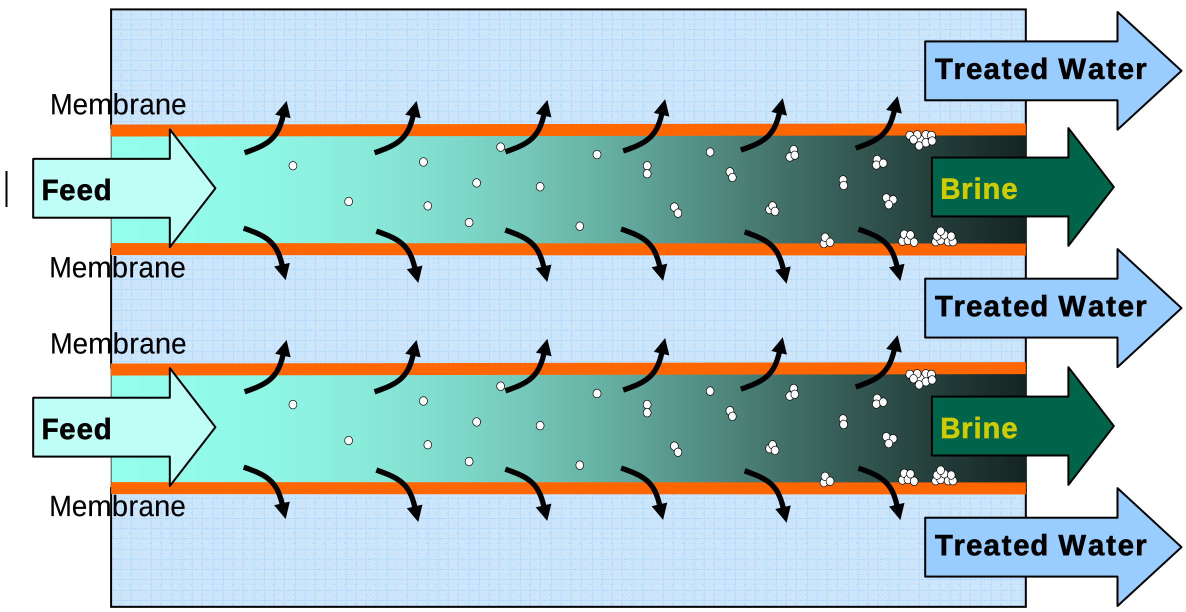


3.1.1 Reverse Osmosis

Reverse osmosis (RO) consists of separating water from a saline solution by the use of a semi-permeable membrane and hydrostatic pressure. Reverse osmosis is a useful separation method since it permits the passage of water and rejects the passage of most ions and molecules other than water. Reverse osmosis is used to purify water and remove salts and other impurities in order to improve the color, taste or properties of the fluid.

Most reverse osmosis technology uses a process known as crossflow to allow the membrane to continually clean itself. As some of the fluid passes through the membrane the rest continues downstream, sweeping the rejected species away from the membrane. (See Figure 3-2) The process of reverse osmosis requires a driving force to push the fluid through the membrane, and the most common force is pressure from a pump. Higher pressures result in a larger driving force. As the concentration of the fluid being rejected increases, the driving force required to continue concentrating the fluid increases. Typical operating pressures for brackish water are 200-300 psi.

Figure 3-2: Reverse Osmosis Process Schematic



Reverse osmosis is capable of rejecting bacteria, salts, sugars, proteins, particles, dyes, and other constituents that have a molecular weight of greater than 150-250 daltons. The reverse osmosis separation is aided by electrical charges. This means that dissolved ions that carry a charge, such as salts, are more likely to be rejected by the membrane than those that are not charged, such as organics. The larger the charge and the larger the molecule, the more likely it will be removed from the water.

Water undergoing reverse osmosis may need to be pre-treated to remove larger particles to prevent clogging of the membranes and reduce membrane maintenance. Pre-treatment of groundwater sources is typically limited to simple in-line filtration. However, surface water sources will almost always require some kind of significant pre-treatment to remove suspended particles.

3.1.2 Electrodialysis

Electrodialysis is a membrane process in which ions are transported through a semi-permeable membrane under the influence of an electric potential. The membranes are cation or anion-selective, which means that either positive ions or negative ions will flow through. Cation-selective membranes are negatively charged, rejecting negatively charged ions and allowing positively charged ions to flow through. Anion-selective membranes have a positive charge, and allow only negatively charged ions to pass. By placing multiple membranes in a stack, which alternately allow positively or negatively charged ions to flow through, the ions can be removed from water.

In some columns concentration of ions will take place and in other columns ions will be removed. The concentrated saltwater flow is circulated until it has reached saturation. At this point the flow is discharged.

This technique can only remove ions from water. Particles that do not carry an electrical charge are not removed. Sometimes pre-treatment is necessary before the electrodialysis can take place. Suspended solids with a diameter that exceeds 10 mm need to be removed, or else they will plug the membrane pores. There are also substances that are able to neutralize a membrane, such as large organic anions, colloids, iron oxides and manganese oxide. These disturb the selective effect of the membrane. Pre-treatment methods, which aid the prevention of these effects are activated carbon filtration (for organic matter), flocculation (for colloids) and filtration techniques.

3.1.3 Other Technologies

Technologies that have been used for removing salts and minerals from the water also include ion exchange and thermal distillation. These technologies have been used widely in industrial applications and in removing specific contaminants such as nitrate or perchlorate.

Ion Exchange

Ion exchange is a reversible chemical reaction wherein an ion from a water stream is exchanged for a similarly charged ion attached to an immobile solid particle. These ion exchange particles are either naturally occurring inorganic zeolites or synthetically produced organic resins. The synthetic organic resins are the predominant type used today because their characteristics can be tailored to specific applications.

In a water ion exchange process, the resins exchange hydrogen ions (H^+) for the positively charged ions (such as nickel. copper, calcium and sodium) and hydroxyl ions (OH^-) for negatively charged sulfates, chromates and chlorides. Because the quantity of H^+ and OH^- ions is balanced, the result of the ion exchange treatment is relatively pure, neutral water. Ion exchange resins are classified as cation exchangers, which have positively charged mobile ions available for exchange, and anion exchangers, whose exchangeable ions are negatively charged. Both anion and cation resins are produced from the same basic organic polymers. Resins can be broadly classified as strong or weak acid cation exchangers or strong or weak base anion exchangers.

Thermal Distillation

Thermal distillation is the oldest method of desalination but is not typically used for public water supply in the United States. Distillation is a phase separation method where saline water is heated to produce water vapor, which is then condensed to produce fresh water. This distillation process operates on the principle of reducing the vapor pressure of water within the unit to permit boiling to occur at lower temperatures, without the use of additional heat. Distillation units routinely use designs that conserve as much thermal energy as possible by interchanging the heat of condensation and heat of vaporization within the units. The major energy requirement in the distillation process is the heat for vaporization of the feed water.

3.2 Desalination Concentrate Disposal

All desalination processes produce two liquid streams: the desalinated product water and a second stream containing the salts and other contaminants separated from the product water, referred to as reject, brine or concentrate. Concentrate disposal represents a significant challenge to most desalination operations. The concentrate is still mostly water (98-99.5% by weight) but is unfit for most uses and many potential discharge locations. It represents a significant fraction of the original water source (10-35%) and so its disposition is far from trivial, especially for large projects. Typical disposal alternatives are described in the following paragraphs.

3.2.1 Evaporation

In a dry area such as West Texas, it is natural to consider evaporation for disposal of unwanted water, and it is a viable alternative for small quantities. Some devices such as mechanical "misters" and mirrors for concentrating solar energy have also been used to enhance natural evaporation. However, for large quantities of concentrate such as those contemplated in this project, the area required for evaporation would be very large, probably hundreds of acres. Evaporation reservoirs would require a synthetic liner to prevent contamination of shallow groundwater, and periodic dredging would likely be required to remove accumulated solids. Because of these factors, it does not appear that evaporation would be feasible as the primary disposal method for this project, although storage reservoirs may be beneficial in managing concentrate disposal, and some beneficial evaporation will occur during storage.

3.2.2 Discharge

Historically, most desalination concentrate has been discharged to the ocean, a sanitary sewer system, or to a stream. This is the simplest and most economical form of disposal, and is preferable when a suitable discharge location is available. However, potential receiving streams in the San Angelo vicinity flow into water supply reservoirs, and would not be compatible with brine discharges.

3.2.3 Dedicated Disposal Wells

Deep saline aquifers have been used in many locations for disposal of various waste streams, including oil field brines, cooling water blowdown, and desalination concentrate. Where favorable conditions exist, this method is attractive due to its minimal impact on the environment and potentially large capacity to receive liquid wastes. Deep well injection has been the disposal method of choice for oil extraction operations due to the industry's familiarity with underground operations and a favorable regulatory framework. Unfortunately, this regulatory framework does not extend to the water industry, where permitting of injection wells is a lengthy and expensive process. The flows from large-scale desalination projects are also significantly larger than typical waste flows from oil operations, complicating the transfer of injection experience. There is growing political pressure to grant desalination concentrate wells more favorable permitting conditions, consistent with those in the petroleum industry. If successful, this should make dedicated disposal wells more feasible in the future.

3.2.4 Conjunctive Use with Oil Field Operations

A promising variant of disposal wells is the joint use and disposal of concentrate in oil extraction operations. Some of these operations use significant quantities of water in oil field flooding operations, which enhance oil well recovery and productivity. Depending on the location, production status, and interest of such operations, this may be a viable disposal alternative. The Texas Water Development Board has provided research to identify opportunities for collaboration between the water and petroleum industries and map/inventory operations which might accommodate concentrate disposal[6].

3.2.5 Zero Liquid Discharge

Technology is also available which can recover additional water from desalination concentrate, increasing the yield from the original source and greatly reducing the volume of waste for disposal. For larger systems, such technology typically consists of a brine concentrator, which distills water from the concentrate stream through a combination of thermal energy and pressure manipulation. If a solid waste output is required, the resulting brine can be further reduced using a crystallizer, which requires additional energy to evaporate sufficient water to form solid salt crystals. These processes have primarily been used for disposal of cooling tower blowdown, but have also been used for desalination concentrate. The equipment is quite expensive and has high energy requirements, so is typically used only where other options do not prove feasible. This option has the advantage of yielding additional high-purity water. It is unlikely that zero discharge technology will be attractive for this project, but it does establish an upper limit on disposal costs, since it can be placed almost anywhere if sufficient energy is available.

3.3 Conclusions

For the capacity and water quality conditions anticipated for this project, reverse osmosis has been identified as the preferred process. This process has been assumed for the development of probable costs in this report. The cost estimates assume that disposal of concentrate will be by dedicated disposal wells, although opportunities for conjunctive use with oil field operations should be considered if available. The following chapter examines local geologic conditions and permitting to be considered with respect to using deep-well injection for disposal.

4 Underground Concentrate Disposal

4.1 Introduction

Two types of underground disposal options have been considered for the 1.5 – 3.0 MGD of desalination concentrate expected to be produced by the proposed project:

- Conjunctive use with oil field operations, and
- Dedicated disposal wells.

Conjunctive use with oil field operations, discussed in Section 4.2, uses the concentrate as “make-up” water in oil-field secondary recovery operations. This would involve injecting the concentrate into existing oil wells under a Class II injection well permit. This option would likely only be used to reduce the volume disposed of by other means, as the fluid volumes required by oil-field operators are smaller than those that would be produced by a 5 or 10 MGD desalination plant.

Using dedicated disposal wells requires a Class I or Class V injection well permit. The receiving formations in the San Angelo area considered for concentrate injection are discussed in Section 4.3. Permitting paths for Class I and Class V injection wells are reviewed in Section 4.4.

4.2 Oil and Gas Well Injection in the San Angelo Area

Oil and gas wells bring brine to the surface in production operations and often have a Class II permit to inject this water for disposal or secondary recovery. Additional “make-up” water for use in secondary recovery operations is obtained from both potable and non-potable water supplies. Mace, et al.[6] have suggested injecting desalination concentrate into Class II-permitted injection wells as make-up water for secondary recovery. Using concentrate as make-up water in this way would reduce the amount of concentrate required to be disposed of in dedicated concentrate disposal facilities.

Table 4-1 presents the most recent (2002) Class II injection volumes available in the San Angelo area by county. Total volumes injected in each of Coke, Crockett, Irion, Reagan, and Sterling counties are comparable to the volumes that would be produced by desalination facilities. A 5 MGD desalination plant is expected to produce approximately

1.5 MGD of concentrate, or 13 million barrels per year. A 10 MGD plant would produce about 3.0 MGD of concentrate, or 26 million barrels per year. These injection data are from Texas Railroad Commission county disposal records.

Table 4-1: Total Class II Injection Volume in Selected Counties in 2002

County	**Disposal Non-Production Zone** (bbl)	**Disposal Production Zone** (bbl)	**Secondary Recovery** (bbl)	**Total** (bbl)	**Average Total Injection Rate** (MGD)
Coke	557,325	3,742,452	11,505,399	15,805,176	1.82
Crockett	5,032,678	30,216,713	23,722,779	58,972,170	6.79
Irion	427,312	715,545	8,809,516	9,952,373	1.15
Reagan	25,248,487	18,719,281	2,551,002	46,518,770	5.35
Sterling	780,162	1,051,826	8,158,978	9,990,966	1.15
Tom Green	400,090	3,694,687	3,146,513	7,241,290	0.83

bbl - barrels

The secondary recovery injected volumes are the most relevant to a discussion of desalination concentrate as make-up water in oil and gas operations. Approximately 8.8 million barrels were injected into wells in Irion County for secondary recovery operations in 2002, or an average of 1 MGD. Other nearby counties that also had large disposal volumes were (in average MGD): Coke, 1.3 MGD; Crockett, 2.7 MGD; and Sterling, 0.9 MGD.

These aggregate volumes suggest that some significant portion of the concentrate produced by a desalination plant could be used in secondary recovery operations in the area, reducing the volume to be disposed of by other methods. Fluctuations in make-up water demand could be buffered with a storage lagoon or tank. However, the infrastructure required to deliver large volumes of water to the secondary recovery locations may make this option less cost-effective than dedicated disposal facilities.

The locations, injection formations, and injection depths for Class II wells in the San Angelo area are shown in Figure 4-1.

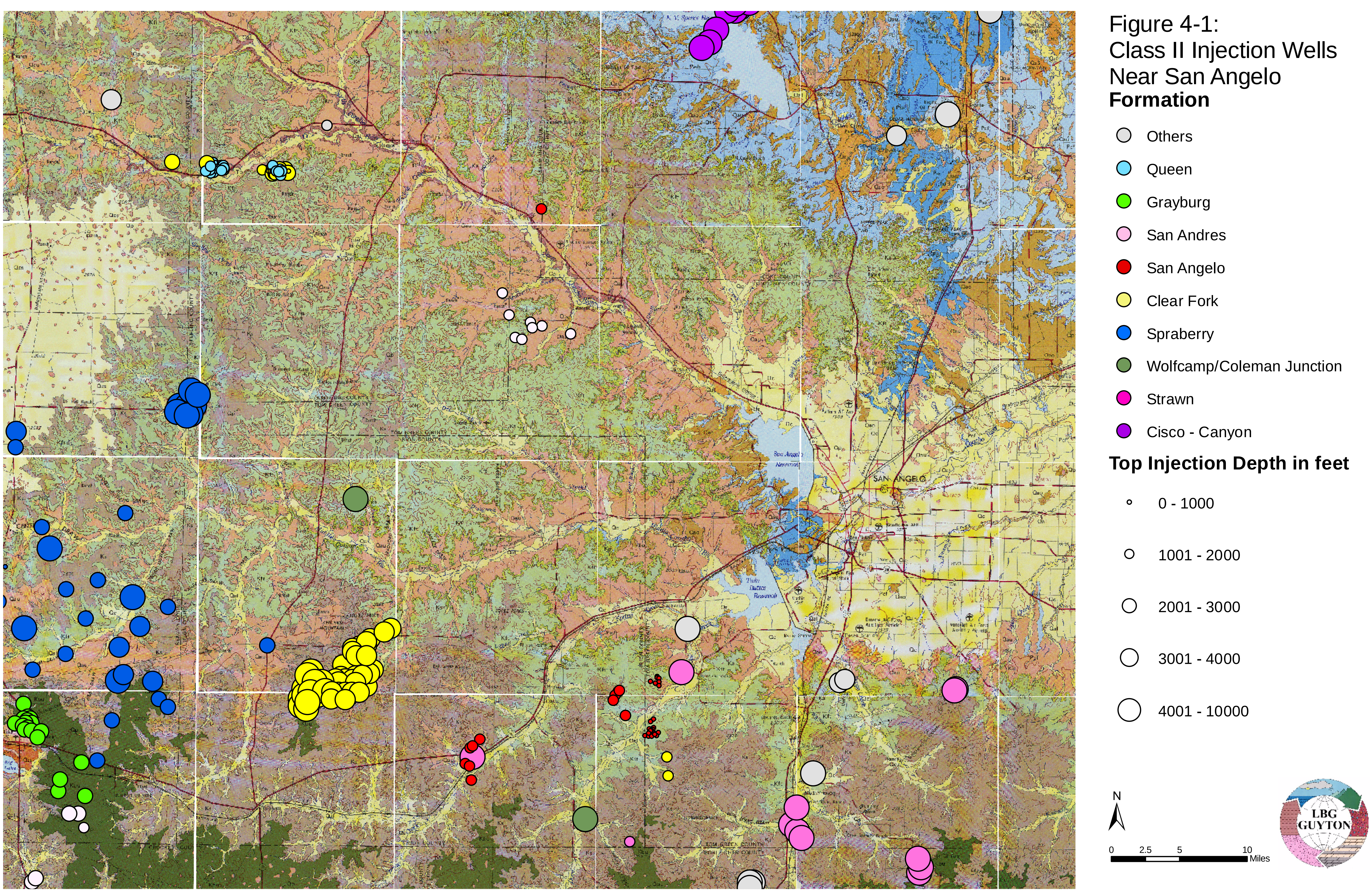


Figure 4-1:
Class II Injection Wells
Near San Angelo

4.3 Possible Concentrate Injection Formations in the San Angelo Area

4.3.1 San Angelo Formation

The San Angelo Sandstone is the lowermost formation of the Permian Pease River Group and consists of up to 250 feet of red sandstone, quartz conglomerate, and shale. About 30 water wells are completed in the San Angelo Sandstone on or near the outcrop in north-central and south-central Tom Green County. Most of these are low-yielding wells for domestic and livestock use. One small public supply well in northern Tom Green County yields 30 gpm. Available water quality records indicate a moderately brackish water from these wells, with a total dissolved solids content ranging from 2,000 to 4,000 mg/L.

Several oil fields in southwestern Tom Green County and southeastern Irion County produce from the San Angelo Sandstone, downdip of the areas that are currently used for water supply. Class II injection wells in these fields are permitted for low volumes (less than 10 gpm) of injection into the San Angelo Sandstone (Figure 4-1). Reported permeabilities for these fields are low, generally less than 100 millidarcies.

The depth to the top of the San Angelo Sandstone ranges from about 800 feet near Knickerbocker in western Tom Green County to about 1,700 feet near Mertzon in Irion County. Elevation contours for the top of the San Angelo Sandstone are shown in Figure 4-2.

Total dissolved solids concentrations from oil-field produced water in the San Angelo Sandstone are given in Table 4-2. These down-dip waters in the San Angelo Sandstone are quite saline, with total dissolved solids concentrations from about 49,000 ppm to about 104,000 ppm.

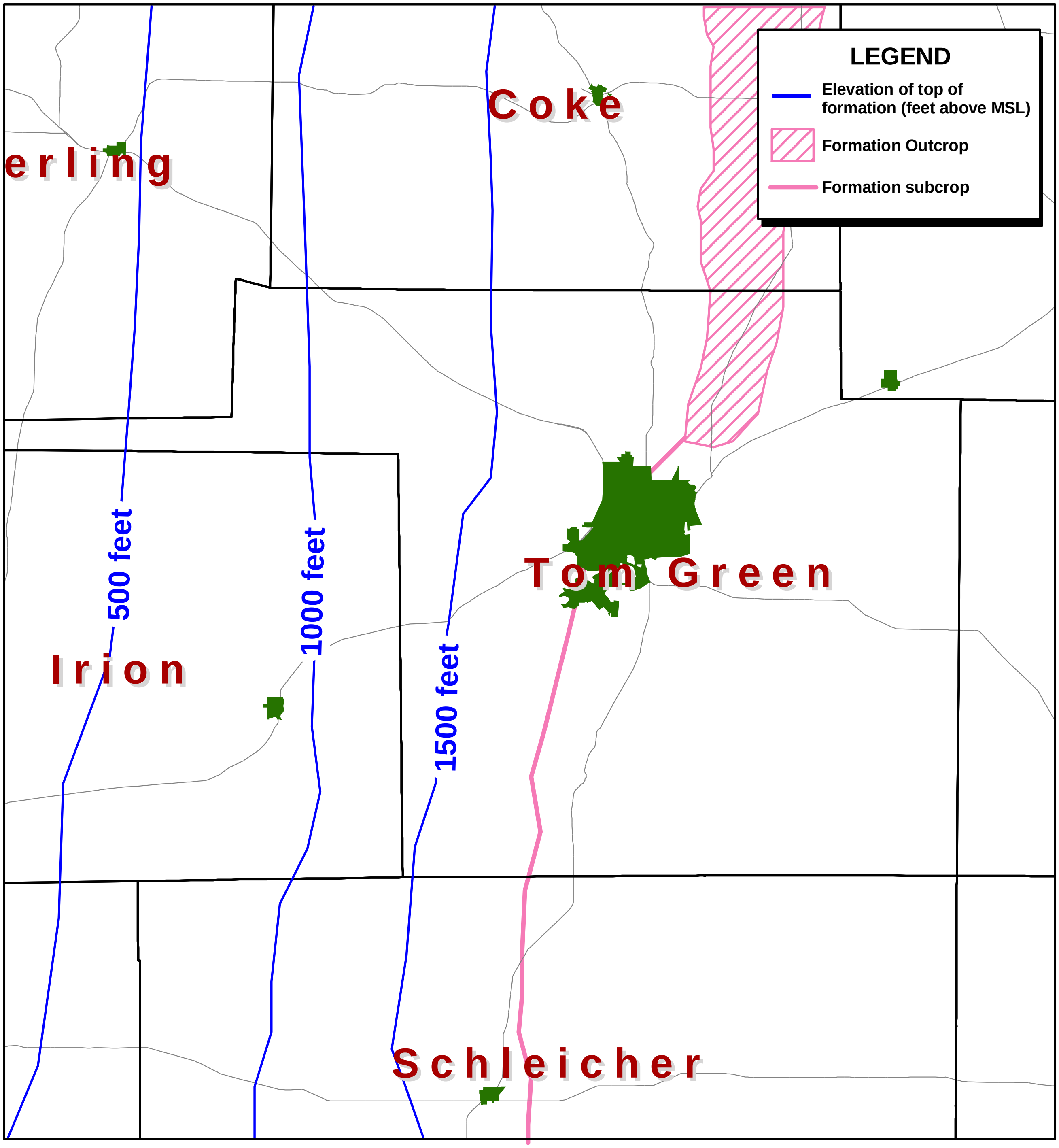


Figure 4-2: Approximate Elevation of the top of the San Angelo Formation

Table 4-2: Total Dissolved Solids Concentrations, Oil-Field Produced Water, San Angelo Sandstone

County	**Formation**	**Number of Samples**	**Average TDS** (mg/L)	**Min TDS** (mg/L)	**Max TDS** (mg/L)
Coke	San Angelo	11	84,918	59,662	103,599
Irion	San Angelo	10	69,242	48,937	75,411
Sterling	San Angelo	2	82,123	81,881	82,365
Tom Green	San Angelo	1	81,431	81,431	81,431

Geophysical logs indicate a moderate potential for injection in the San Angelo Sandstone in Tom Green and Irion County, with a productive thickness of about 70 feet. Based on Class II injection volumes, water well production, and productive thicknesses indicated on geophysical logs, it is unlikely that large flows can be injected in any one well completed in the San Angelo Sandstone. The presence of water wells completed in the San Angelo Sandstone in central Tom Green County limits the geographic area available for injection to locations west of the Twin Buttes Reservoir in Tom Green County.

4.3.2 Clear Fork Group

The Clear Fork Group consists of the Choza, Vale, and Arroyo Formations. The Clear Fork Group outcrops along the eastern border of Coke County and extends into western Runnels County. These formations, in combination with the overlying Leona sand and gravel, comprise the Lipan Aquifer in eastern Tom Green County, southeastern Coke County and southwestern Runnels County. The Clear Fork is about 1,200 feet thick in western Tom Green County and about 1,500 feet thick in Irion County. Geophysical logs indicate the total thickness of the productive limestones (primarily the Bullwagon Dolomite and the Standpipe Limestone) is about 150 feet.

Numerous wells are completed on the outcrop of the Clear Fork Group in eastern Tom Green County, southeastern Coke County and southwestern Runnels County. Many of these wells are very productive, yielding between 100 to 1,000 gpm of slightly brackish water.

A large oil field produces from the Clear Fork Group in central Irion County (Figure 4-1). Many of these wells are permitted for low-volume Class II injection at about 500 - 700 bbl/day (about 15 – 20 gpm). The reported permeability for this field is also quite low, less than 10 millidarcies.

The depth to the productive limestones of the Clear Fork ranges from about 1,300 feet in western Tom Green County to about 3,500 feet in central Irion County. Elevation contours for the top of the productive intervals of the Clear Fork are shown in Figure 4-3.

Total dissolved solids concentrations from oil-field produced water in the Clear Fork Group are given in Table 4-3. In contrast to the slightly brackish waters in water wells on the Clear Fork outcrop, oil-field waters produced from the Clear Fork are moderately to strongly saline, ranging from about 11,000 mg/L to about 93,000 mg/L in total dissolved solids concentration.

Table 4-3: Total Dissolved Solids Concentrations, Oil-Field Produced Water, Clear Fork Group

County	**Formation**	**Number of Samples**	**Average TDS** (mg/L)	**Min TDS** (mg/L)	**Max TDS** (mg/L)
Irion	Clear Fork	5	77,223	37,195	93,153
Sterling	Clear Fork	4	54,817	11,564	78,575
Tom Green	Clear Fork	1	16,268	16,268	16,268

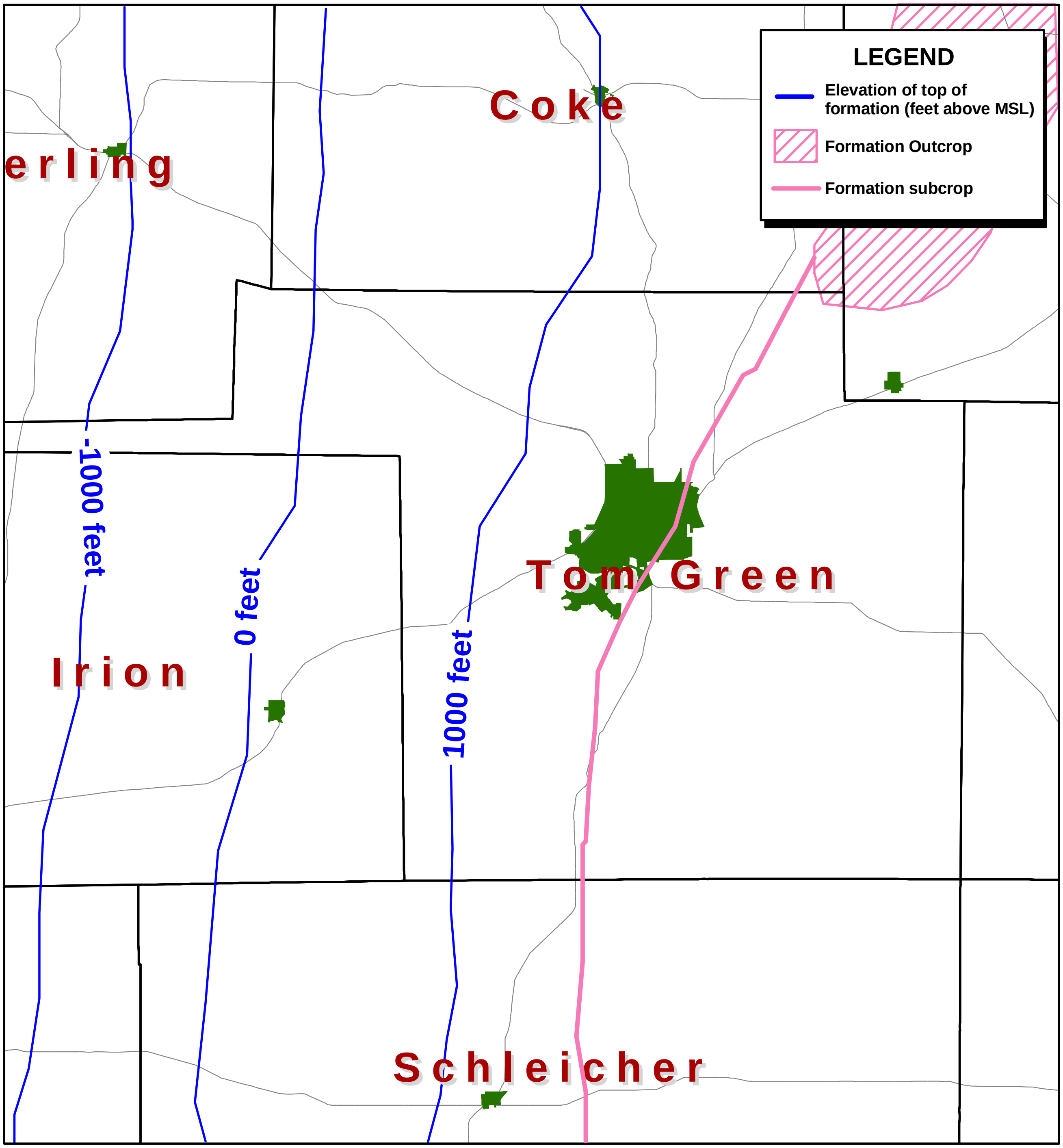


Figure 4-3: Approximate Elevation of the top of the Clear Fork Formation

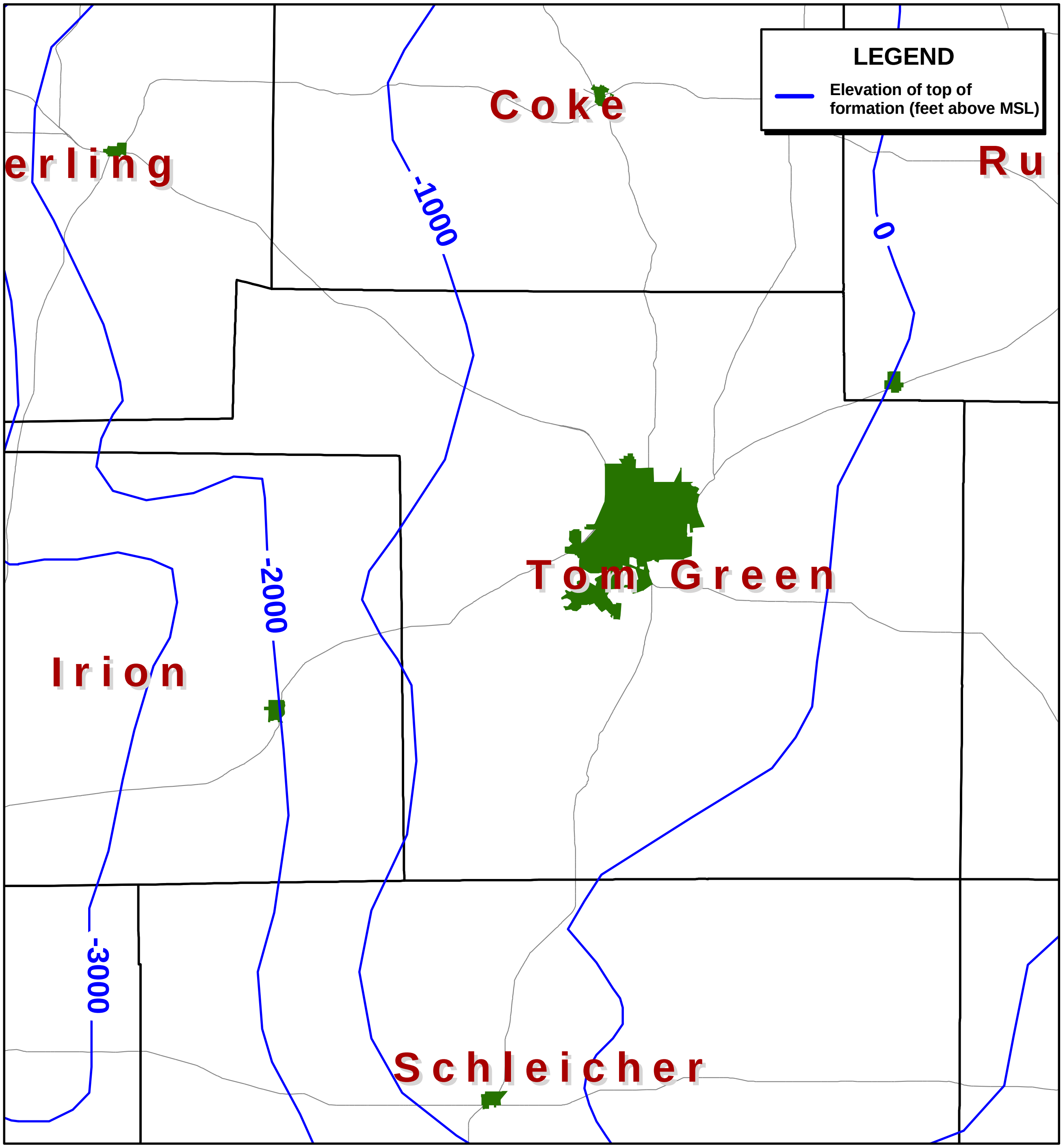
Geophysical logs indicate a moderate potential for injection in the Clear Fork in Tom Green and Irion Counties, with perhaps 150 feet of productive thickness. The increasing salinity of water in down-dip sections is often correlative with low permeability in limestone formations. Combined with the low permeability reported in oil field records in Irion County, this suggests that the potential for large volumes of injection becomes poor in the Clear Fork west of Tom Green County. Water wells completed in the Clear Fork further constrain the locations available for Clear Fork injection to a geographic area west of the San Angelo City limits.

4.3.3 Lower Wichita-Albany Group

The Wolfcampian-age Admiral and Coleman Junction Formations are the lowermost formations of the Wichita-Albany Group. From the outcrop in Coleman Counties, these formations dip into the subsurface and reach a total thickness of about 250 feet in Tom Green and Irion Counties. The stratigraphic terms of “Wolfcamp” and “Coleman Junction” are often used interchangeably.

These formations can be reached at about 2,300 feet deep in central Tom Green County, 2,900 feet deep in western Tom Green County, and about 3,500 feet deep in eastern Irion County. The estimated elevation of the top of these Wolfcampian-age formations in the San Angelo area is shown in Figure 4-4.

Porosities in the Wolfcamp/Coleman Junction in west Texas range from 5 to more than 25 percent, and permeabilities range from 1 millidarcy to more than 1 darcy. There are two wells permitted for Class II injection into the Wolfcamp/Coleman Junction: one brine injection well and one gas injection well. The Class II brine injection well in the Wolfcamp/Coleman Junction is located in southeastern Irion County. This well is permitted to inject 3,500 bbl/day (102 gpm) into a 50-foot interval at the top of the Wolfcamp. The Class II gas injection well, in northern Irion County, is permitted to inject 2,500 million cubic feet per day into the Wolfcamp. The injection interval for this well is 82 feet in length.



Contours based on Core Laboratories (1972)

Figure 4-4: Approximate Elevation of the top of the Wolfcampian Lower Wichita-Albany Group

Total dissolved solids concentrations from oil-field produced water in the Wolfcamp are given in Table 4-4. There is a large variability in these results, ranging from a low of 2,300 mg/L to a high of about 180,000 mg/L.

Table 4-4: Total Dissolved Solids Concentrations, Oil-Field Produced Water, Wolfcampian Lower Wichita-Albany Group

County	Formation	Number of Samples	Average TDS (mg/L)	Min TDS (mg/L)	Max TDS (mg/L)
Irion	Wolfcamp	1	8,901	8,901	8,901
Schleicher	Wolfcamp	1	183,266	183,266	183,266
Sterling	Wolfcamp	14	65,352	2,393	130,456

Geophysical logs in Tom Green and Irion County show a positive response at the top of the Wolfcamp/Coleman Junction, and indicate productive thicknesses of about 200 feet in eastern Irion County and about 300 feet in western Tom Green County. The potential for significant injection volume in the Wolfcamp appears highest in Tom Green County. Further, there are no water wells in the Wolfcamp/Coleman Junction in the San Angelo area that limit the injection location, as is the case with other injection formations near San Angelo.

The Wolfcamp/Coleman Junction is considered the most feasible strata for concentrate disposal. To further evaluate the Wolfcamp/Coleman Junction disposal potential the flows and pressures associated with injection into Wolfcampian-age formations near San Angelo were estimated. Using TCEQ's MASIP program, a maximum allowable surface injection pressure of 607 psi was calculated. In accordance with TCEQ practice, this injection pressure includes a 100-psi factor of safety and excludes tubing friction losses. The depth to the top of the injection interval used in this calculation was 2,700 feet. This corresponds to the approximate depth to the top of the Wolfcamp in the suggested locations for concentrate disposal (Figure 5-1). Other assumptions included a formation TDS of 80,000 mg/L, a concentrate TDS of 12,000 mg/L, an initial wellhead pressure of 60 psi, and a porosity of 10%.

Based on available literature[7] and in oil and gas data from the Texas Railroad Commission, formation flow capacities for the Wolfcamp/Coleman Junction range from about 12,500 millidarcy-feet to 100,000 milidarcy-feet. Assuming a formation flow capacity of 12,500 millidarcy-feet and a maximum allowable surface injection pressure of 607 psi, 150 gpm could be injected into the formation. At 150 gpm, five to seven injection wells would be needed for a 5-MGD desalination plant. At the same maximum surface injection pressure and a formation flow capacity of 100,000 millidarcy-feet, 1,000 gpm could be injected into the formation. At 1,000 gpm only one injection well would be required for a 5-MGD desalination plant.

The maximum allowable surface injection pressure (and therefore the flow rate) can be augmented by increasing the depth to the top of the injection interval. The well completion would be deeper if the upper part of the planned injection interval has poor flow capacity. Alternatively, or perhaps additionally, the location of the concentrate injection wells could be moved further downdip in the Wolfcamp (west) and to an area of higher surface elevation. Other factors being equal, this would result in higher injection rates.

4.4 Requirements for Class I and Class V Injection

Underground injection wells are classified in Texas Administrative Code Title 30 §331.11 and are regulated by the Texas Commission on Environmental Quality (TCEQ). An injection well constructed for the disposal of desalination concentrate would be permitted as either a Class I or a Class V well, depending primarily on the native water quality of the receiving formation and the formations above and below it. The specific constraint is whether the native water quality of the formations of concern have a total dissolved solids concentration less than 10,000 mg/L, in which case it is considered an underground source of drinking water (USDW).

4.4.1 Class I Injection Wells

Class I injection wells are industrial and municipal hazardous and nonhazardous waste disposal wells that inject fluids beneath the lower-most formation which contains an USDW within one-quarter mile of the wellbore. Class I permits have stringent well design requirements and require a lengthy (up to 360 days) review period. If the receiving formation is not an USDW and there is an USDW above the receiving formation, then an injection well will most likely take a Class I permit path, even if the injectate is non-hazardous. The rules concerning Class I injection are intended to protect the upper USDW from leakage of degrading water from below – whether that degrading water is natural non-USDW formation water or injectate.

4.4.2 Class V Injection Wells

Class V injection wells inject nonhazardous fluids from a variety of different sources, and usually inject into or above formations that contain USDWs. Class V injection permits have less stringent construction requirements and require a shorter review period. In order for an injection well to be permitted as Class V the waste stream must be nonhazardous and not degrade the quality of the receiving formation with regard to any regulated constituent. If the injectate will degrade the quality of the USDW, dilution of the injectate can be used to satisfy this non-degradation requirement.

An injection well may also be permitted as Class V if:

- The receiving formation is not considered an USDW,
- No formations above or below the receiving formation are considered USDWs, and
- No hydrogeologic factors exist that may indicate a potential for interaction with an USDW.

TCEQ is currently considering revisions to their injection well rules to better accommodate municipal desalination projects.

5 Recommended Facilities

The conceptual evaluation presented in this report indicates that the Whitehorse aquifer is a promising source for desalination, but costs will vary significantly with three key factors:

- Well field location,
- Groundwater quality, and
- Aquifer hydrogeologic properties.

Additional groundwater information is needed to confirm the feasibility of producing usable water from the Whitehorse Aquifer.

The conceptual cost estimates developed in this study are based on developing an initial production capacity of five million gallons per day (mgd) of desalinated water, with eventual expansion to 10 mgd. A sensitivity analysis has been conducted to determine the impact of various factors on the project economics, and water quality appears to be the most important variable. The key facilities required to develop the Whitehorse Aquifer are described below.

5.1 Well Field

An extensive well field will be required to produce the desired quantity of water from this source. Assuming an average production capacity of 200-350 gpm per well, a total of 14-26 wells will be required for the initial system, and additional wells can be added to increase capacity as needed. Well spacing and depth will also depend on the findings of the proposed field testing program. An above-ground storage tank is proposed to receive water from the individual wells, providing an opportunity to intercept suspended solids and allowing more consistent transmission pumping from the well site to the treatment facility. Additional information about well field facilities may be found in Appendix D.

5.2 Transmission Pipeline

A transmission pipeline will convey water from the well field to the desalination facility. Based on an ultimate net production of 10 mgd, a 30-inch pipeline is assumed from the well field storage tank to the treatment facility. A transmission pump station will be required at the well field. Additional information on proposed facilities may be found in Appendix D.

5.3 Treatment System

A reverse osmosis treatment facility is proposed for desalination of the groundwater. Reverse osmosis membranes are arranged in many parallel layers which are then wound in a spiral fashion and placed in a standard pressure vessel. Numerous pressure vessels are arranged in parallel fashion on a modular rack, and racks are added as necessary to achieve the desired capacity. In addition to the membrane racks, the facility will include high pressure feed pumps, chemical feed facilities and system controls, all housed in a common building. Influent and product water storage tanks will be required as well. Additional information on proposed treatment facilities may be found in Appendix D.

Preliminary predictions of groundwater quality include significant concentrations of calcium sulfate (gypsum), which will be an important parameter in determining the percent recovery of water through the reverse osmosis process. Precipitation of calcium sulfate, silica or other scaling minerals limits the allowable concentration in the waste brine, and controls the amount of raw water required to produce a gallon of desalinated water. The recovery is expected to be between 65% and 80%. If the recovery falls below 65% because of high concentrations of calcium sulfate or silica, the project is not likely to be economically viable. Low recoveries result in increased well production requirements, increased transmission pumping, and increased waste disposal, which will significantly increase the cost of implementing the project.

5.4 Concentrate Disposal

As noted in Section 3.2, disposal of the concentrate, or waste brine, is a significant consideration for desalination planning. For the large project contemplated, deep well injection appears to be the most likely disposal method. Disposal wells are likely to have a capacity of 100-200 gpm, and 6-10 wells will probably be required for the initial phase of 5 mgd. Additional information regarding disposal facilities may be found in Appendix D.

5.5 San Angelo Connection

The primary user of desalinated water from the Whitehorse aquifer is expected to be the City of San Angelo, although some smaller systems in the area may also benefit from this source. Two locations appear promising for introducing additional water supplies into the San Angelo system. The first location would be immediately east of Twin Buttes Reservoir, at the north end of the San Angelo system. Raw water from the Spence and Ivie Reservoirs is piped into the city at this point, and travels into the central portion of the city to the treatment plant, where it is blended with water from local reservoirs prior to treatment and distribution. The second location is in western San Angelo. The use of this location as an entry point would likely include blending a large portion of the desalinated water into a finished water storage tank which serves western San Angelo, and piping the remainder to the water treatment plant for blending with the treated surface water prior to distribution.

A detailed evaluation of these entry points is not necessary at this time. Several factors will need to be considered before a decision is made, including well field location, available concentrate disposal locations, inclusion of regional participants, potential desalination of surface water supplies, and growth patterns in San Angelo.

5.6 Probable Costs

Figure 5-1 illustrates two conceptual layouts of facilities for a desalinated groundwater project. Specific facility locations have not been determined at this time; the figure is only intended to show the conceptual arrangement for such a project. A concept-level opinion of probable costs is shown in Table 5-1. Detailed assumptions of the cost opinion and the cost sensitivity analysis are included in Appendix D. The range of probable unit cost is $2.22-3.22 per 1000 gallons. Although this is a significant cost, it appears to be competitive with other identified sources of additional water for San Angelo. The proposed test well program (Appendix C) will allow more accurate estimates of cost and feasibility to be prepared.

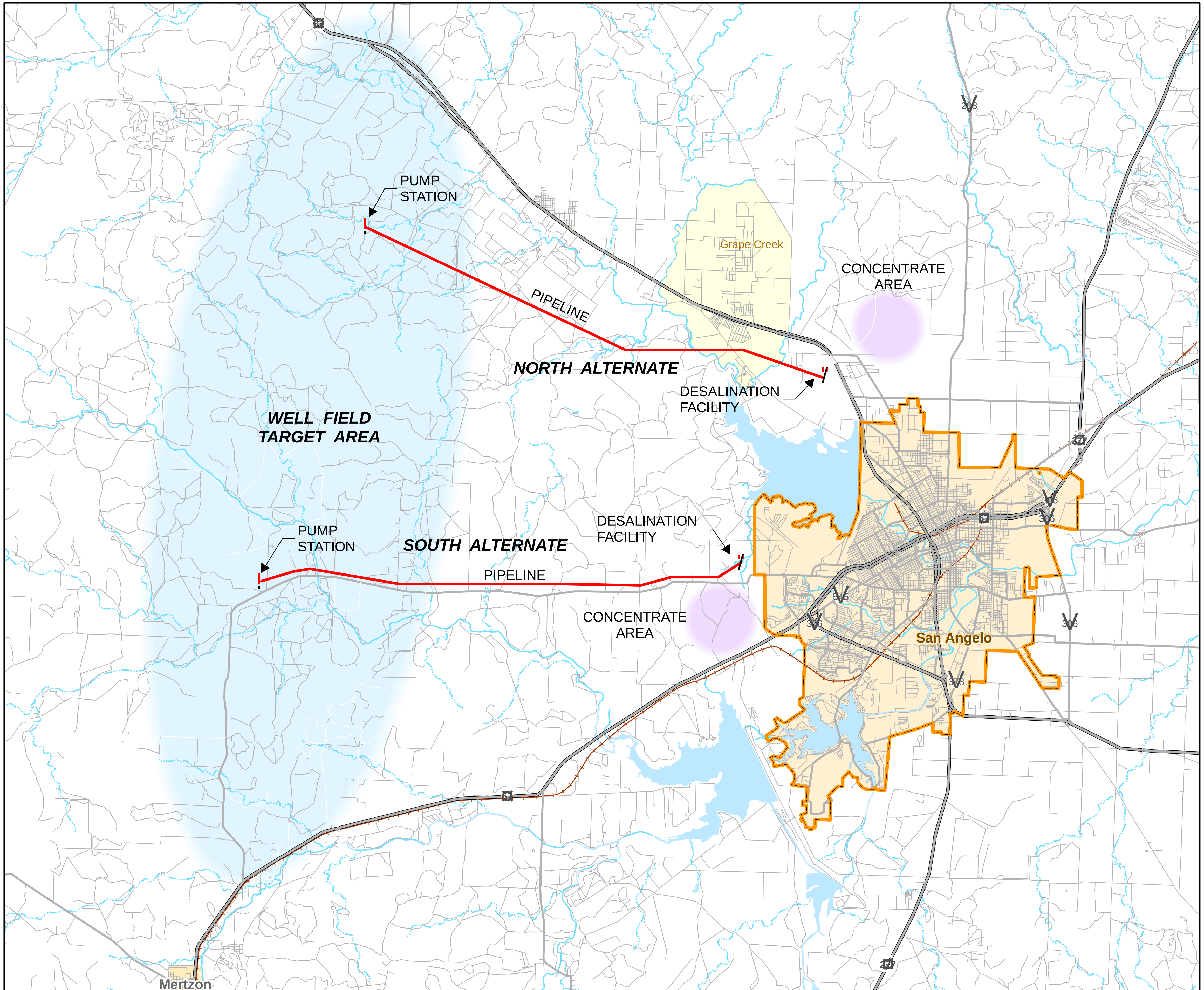


FIGURE 5-1
CONCEPTUAL LAYOUT FOR BRACKISH GROUNDWATER DEVELOPMENT

LEGEND:

- DESALINATION FACILITY
- PUMP STATIONS
- PIPELINE
- CONCENTRATE INJECTION AREA
- WELL FIELD AREA

NOTE: LAYOUTS ILLUSTRATE CONCEPTUAL ARRANGEMENTS AND DO NOT DEPICT SPECIFIC SITING OF PROPOSED FACILITIES

0 1.5 3 6 Miles

Freese and Nichols

Table 5-1: Costs for Desalinated Water from the Whitehorse Aquifer

	5 MGD	**10 MGD**
Supply from Strategy	5,600 acre-feet per year	11,200 acre-feet per year
Total Capital Costs (2005 Prices)	$ 28,921,000	$ 48,008,000
Annual Costs	$ 1,535,000	$ 2,931,000
Unit costs (before amortization)	$ 724 per acre-foot	$ 635 per acre-foot
	$ 2.22 per 1,000 gallons	$ 1.95 per 1,000 gallons
Unit Costs (after amortization)	$ 274 per acre-foot	$ 262 per acre-foot
	$ 0.84 per 1,000 gallons	$ 0.80 per 1,000 gallons

Appendix A

List of References

Appendix A
List of References

[1] Freese and Nichols, Inc. et al.: *Region F Initially Prepared Plan*, prepared for the Region F Water Planning Group, August 2005.

[2] San Angelo City Council, Citizen's Water Advisory Group, San Angelo City Staff: *San Angelo Water Preparing for the Next 50 Years*, February 2004.

[3] Texas Commission on Environmental Quality: Water Availability Model for the Colorado and Brazos Colorado Basins, Full Authorization (Run 3), November 2004.

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[6] Mace, R. E., Nicot, J. -P., Chowdhury, A. H., Dutton, A. R., and Kalaswad, Sanjeev: *Please Pass the Salt: Using Oil Fields for the Disposal of Concentrate from Desalination Plants, in the Future of Desalination in Texas, Volume 2,* Texas Water Development Board Report 363, 2004.

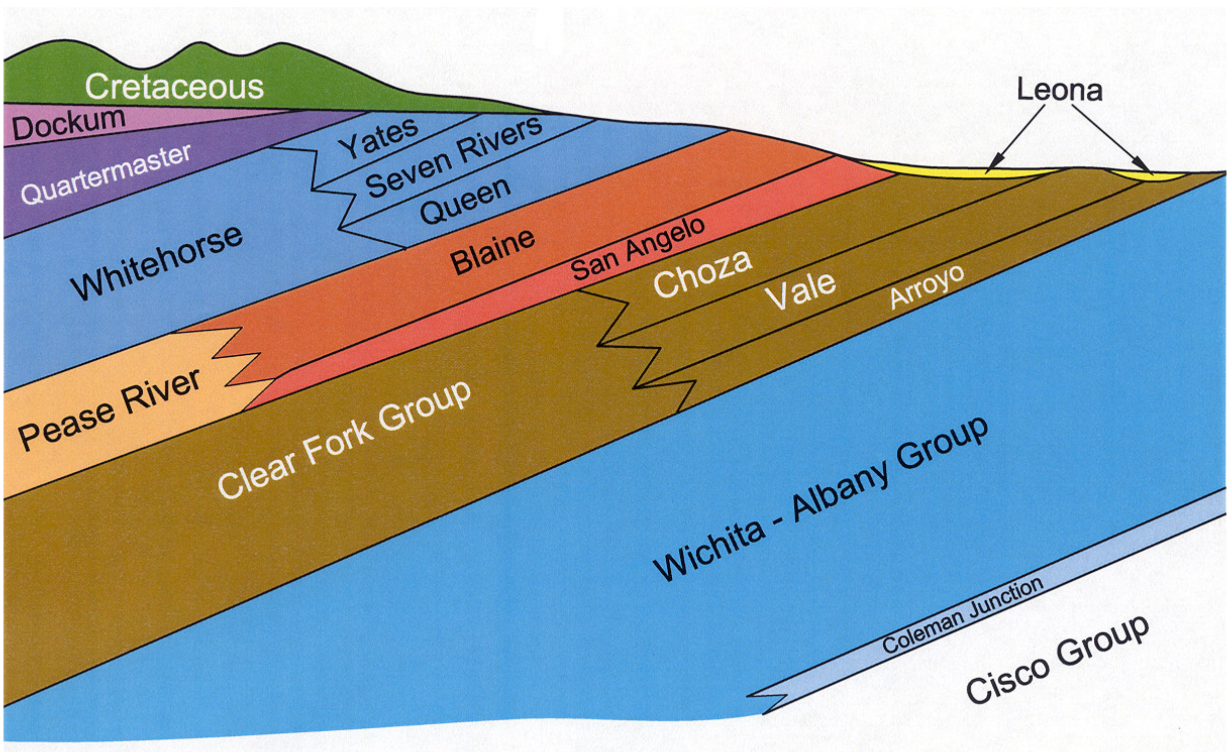
[7] Core Laboratories: *A Survey of the Subsurface Saline Water of Texas*, Texas Water Development Board Report 157, 1972.

Appendix B

An Evaluation of Triassic and Permian Brackish Groundwater Resources in the San Angelo, Texas Area

An Evaluation of Triassic and Permian Brackish Groundwater Resources in the San Angelo, Texas Area

January 2005



Prepared by

LBG-GUYTON ASSOCIATES

Professional Ground-Water and Environmental Engineering Services

A Division of Leggette, Brashears & Graham, Inc.

An Evaluation of Triassic and Permian Brackish Groundwater Resources in the San Angelo, Texas Area

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Prepared by

LBG-GUYTON ASSOCIATES
Professional Ground-Water and Environmental Services
1101 S. Capital of Texas Highway, Suite B-220
Austin, Texas 78746

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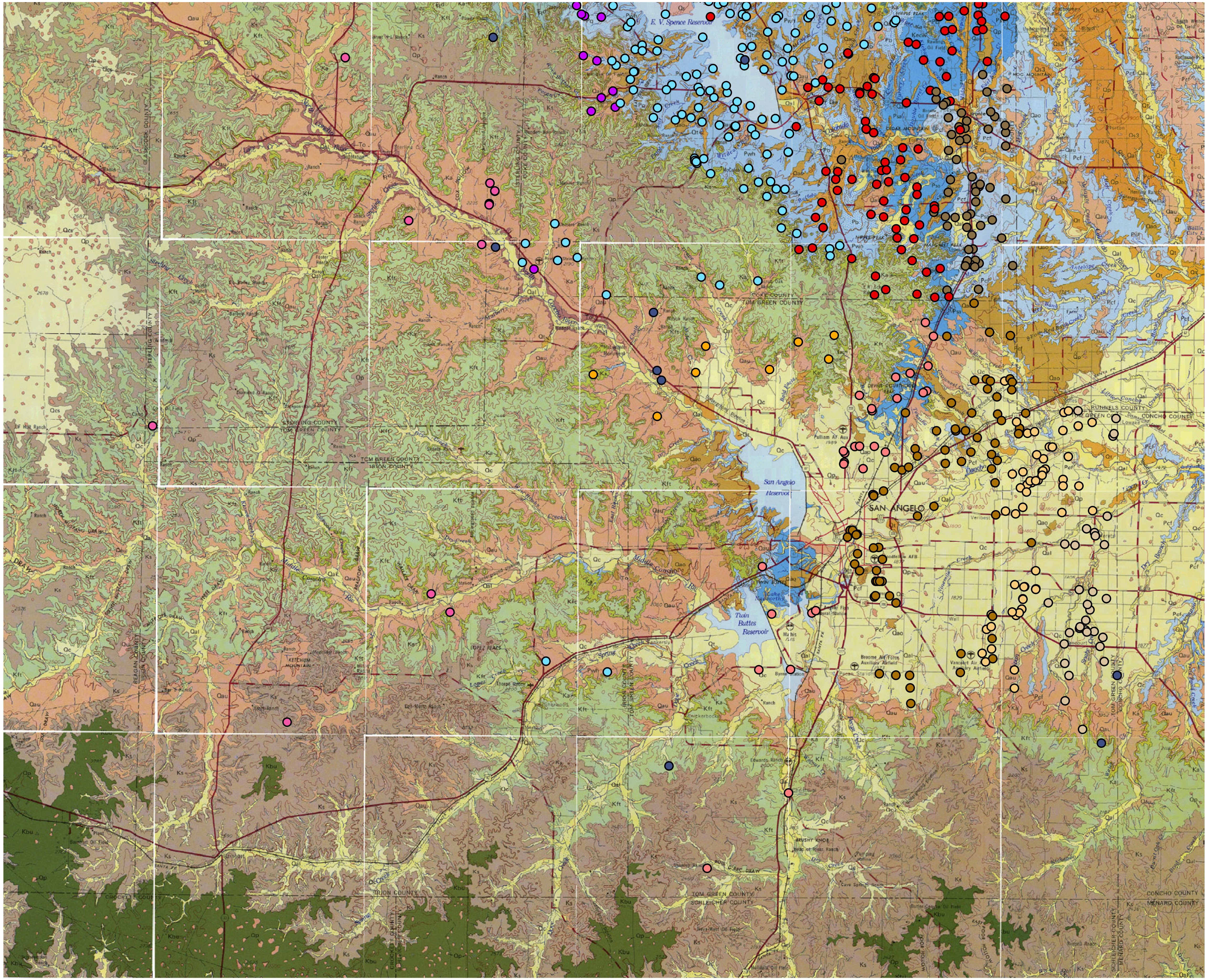
1.0 INTRODUCTION

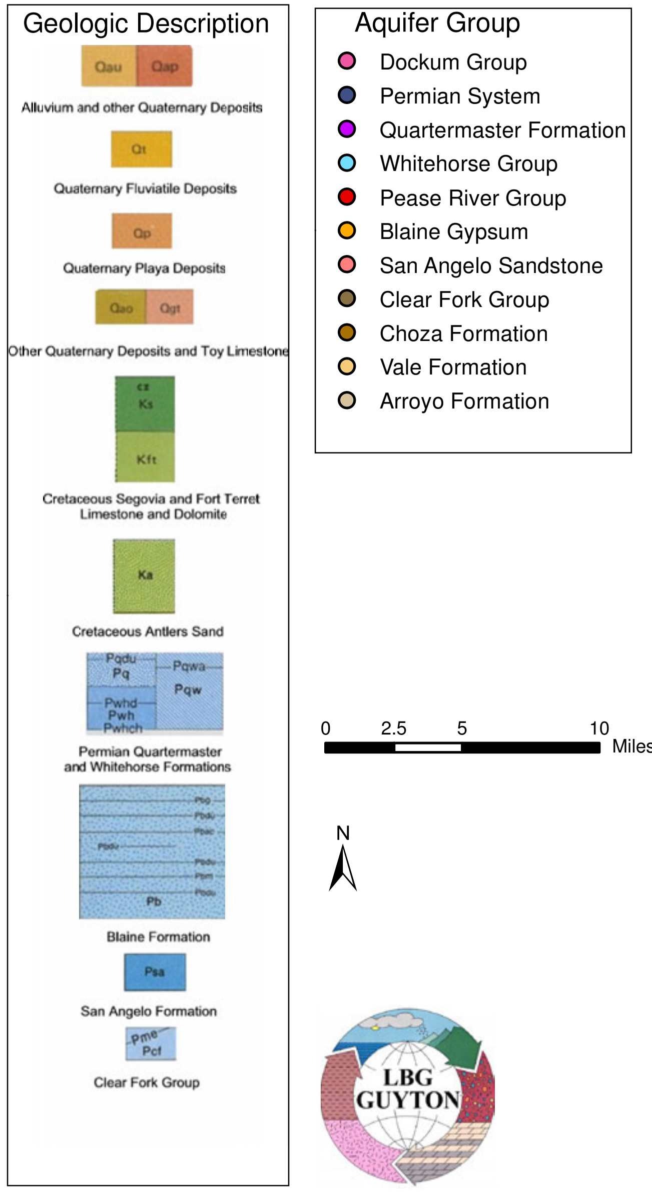
Additional supplies of water in the San Angelo, Texas area may be obtained by the desalination of brackish groundwater. As part of the Region F regional water planning process and the efforts of the Upper Colorado River Authority, an evaluation of Triassic and Permian aquifers in the San Angelo area as a potential source of brackish groundwater was conducted. This report presents the evaluation of these aquifers based on existing well data, results of a pumping test of a shallow Whitehorse Formation well (the Parks well), and analyses of multiple oil field geophysical logs. The report culminates in recommendations for further analysis needed to confirm the viability of each water-bearing formation as a sustainable water supply.

The study area for this investigation is located in an area west and north of San Angelo, as shown in Figure 1, which focuses on parts of Tom Green, Irion, and Coke Counties with small areas overlapping into Runnels and Sterling Counties. Lying on the northern edge of the Edwards Plateau province, the area is characterized by hard Cretaceous limestone hills of the Edwards Plateau incised by valleys formed by the branches and tributaries of the Concho River. Surrounding Spence Reservoir and extending eastward are gently rolling hills formed from outcropping Permian-age formations. The Lipan Flats, a broad, flat plain dominated by farmland lies in the central to eastern portion of the study area.

Ground surface elevations vary across the study area from about 1,500 feet above mean sea level (AMSL) in the east to about 2,500 feet in the west and north. Deeply entrenched spring-fed streams drain the higher elevation bedrock hills while meandering rivers dominate the flat lower elevations. Mesquite, juniper and ash shrubs and brush make up a large portion of the vegetation in the rangeland areas, while riparian vegetation inhabits the area immediately adjacent to the branches of the Concho River.

Figure 1:
Study Area, Surface Geology, and Aquifer Designation of Wells





GEOLOGIC UNITS			
Cretaceous			Edwards
			Antlers
Triassic		Dockum	Santa Rosa
Permian	Ochoan		Quartermaster/Rustler
	Guadalupian	Whitehorse	Yates
			Seven Rivers
			Queen
			Blaine
		Pease River	San Andres
			San Angelo
	Leonardian	Clear Fork	Choza
			Vale
			Arroyo

2.0 APPROACH

In order to accomplish the goal of identifying potential brackish groundwater sources and recommending test hole locations for future analyses, the following tasks were undertaken:

- Existing geologic and hydrologic data, reports, and maps were compiled;
- Pertinent geophysical logs were selected and analyzed;
- Data was GIS formatted and transferred into visual media for analyses; and
- A pumping test was performed on an existing well.

An evaluation of the supporting geohydrologic data was then performed to select test hole sites that have the best potential to encounter optimal subsurface conditions including maximum yield from several potential water-bearing formations, acceptable water quality range, and reasonable depth.

Existing geologic and hydrologic information were identified, compiled, and reviewed. Useful data are available in the form of reports and maps as well as in database format. Texas Water Development Board (TWDB) and United States Geological Survey (USGS) groundwater availability and data reports provide information on historically used aquifers including well locations and construction characteristics, aquifer descriptions, and subsurface geologic cross sections. These reports generally focus on usable quality groundwater sources, and therefore further evaluation was required to interpret conditions within the more brackish portions of the aquifers. The "Brackish Groundwater Manual" prepared for the TWDB by LBG-Guyton was also reviewed. Surface geology is best depicted on the Bureau of Economic Geology San Angelo Geologic Atlas Sheet.

Water well data from the TWDB groundwater database was downloaded and well data was catalogued into hydrologic units that correlate with unit names selected for this report. The well data was then integrated into a GIS mapping program so that specific aquifer characteristics could be examined such as water level elevation, direction of movement, distribution of pumping capacities, and water quality trends.

Because of a lack of subsurface information in the specific area of interest, an evaluation of pertinent geophysical logs was performed. Numerous logged wells in the study area available from the Bureau of Economic Geology and the Texas Commission on Environmental Quality (TCEQ) log libraries, geophysical logs from approximately 80 wells were selected for further analysis. Log types specifically selected for this evaluation are gamma and resistivity. Gamma logs were primarily used to identify depths to the top and bottom (thickness) of individual geologic units and their lithologic (rock type) makeup, while resistivity logs were used to assess the water quality potential in the water-bearing zones. These logs were useful in understanding the subsurface hydrogeologic condition at any location, and the logs assisted in the development of maps and cross sections that depict the lateral extent of the geologic units.

The following brackish groundwater source and test hole site recommendation was developed from the above information and is provided in both text and in simplified illustrations. Specific geologic units in the area that potentially contain variable quantities and quality of brackish groundwater include the Dockum of Triassic age and the various formations that make up the Permian-age Whitehorse, Pease River, Clear Fork, and Wichita-Albany Groups.

3.0 HYDROGEOLOGY

The surface geology in the study area (Figure 1) can be characterized in terms of three general groupings. Geologic units comprising these groupings can also be traced into the subsurface as portrayed in cross section (Figure 2). Relatively shallow, Quaternary-age alluvial deposits form the flood plains along the river branches and overlie the Lipan Flats area east of San Angelo. The Lipan deposits, which can be up to 125 feet thick, consist mostly of gravels and conglomerates cemented with sandy lime and layers of clay. These deposits contain limited amounts of fresh to brackish quality water.

The second geologic grouping is the Cretaceous-age formations of the Edwards Plateau, which outcrop to the north, west, and south, and consist of hard Edwards limestone and underlying Trinity (Antlers) sandstone formations. These Cretaceous formations generally contain fresh groundwater in the limestones and fresh to brackish water in the underlying sandstone unit.

The primary focus of this evaluation and the third geologic grouping consists of Triassic (Dockum) and Permian formations that underlie the Quaternary alluvium and Cretaceous formations and are exposed at the surface (outcrop) immediately to the north of the Lipan Flats. The Permian units include formations of the Quartermaster, Whitehorse, Pease River, Clear Fork, and Wichita-Albany Groups. As shown in the cross-section in Figure 2, these formations dip westward from their outcrop towards the Permian Basin at about 50 feet/mile. The Triassic Dockum is located in the western portion of the study area but does not outcrop within the study area. Figure 3 shows the range of depths to which each well is drilled, and Figure 4 shows the range of water quality expressed in total dissolved solids (TDS) for those wells that have been sampled. Location of selected oil and gas wells with geophysical logs is illustrated in Figure 5.

Considerable variation occurs within the geologic formation terminology used in the numerous reports in the area; thus the geologic nomenclature used in this report represent a logical compromise of names.

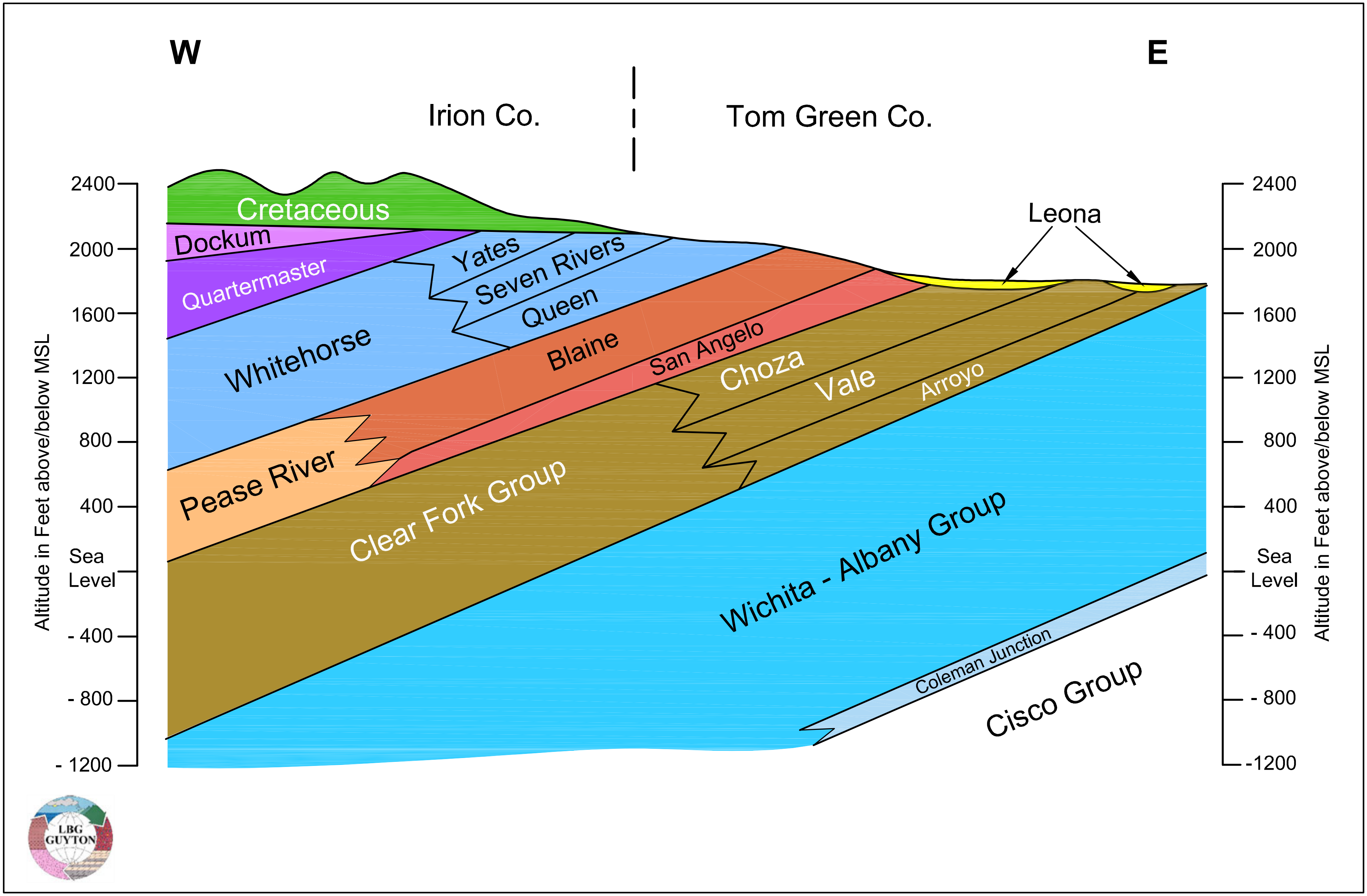


Figure 2: West to East Geologic Cross Section

Figure 3:
Depth of Wells

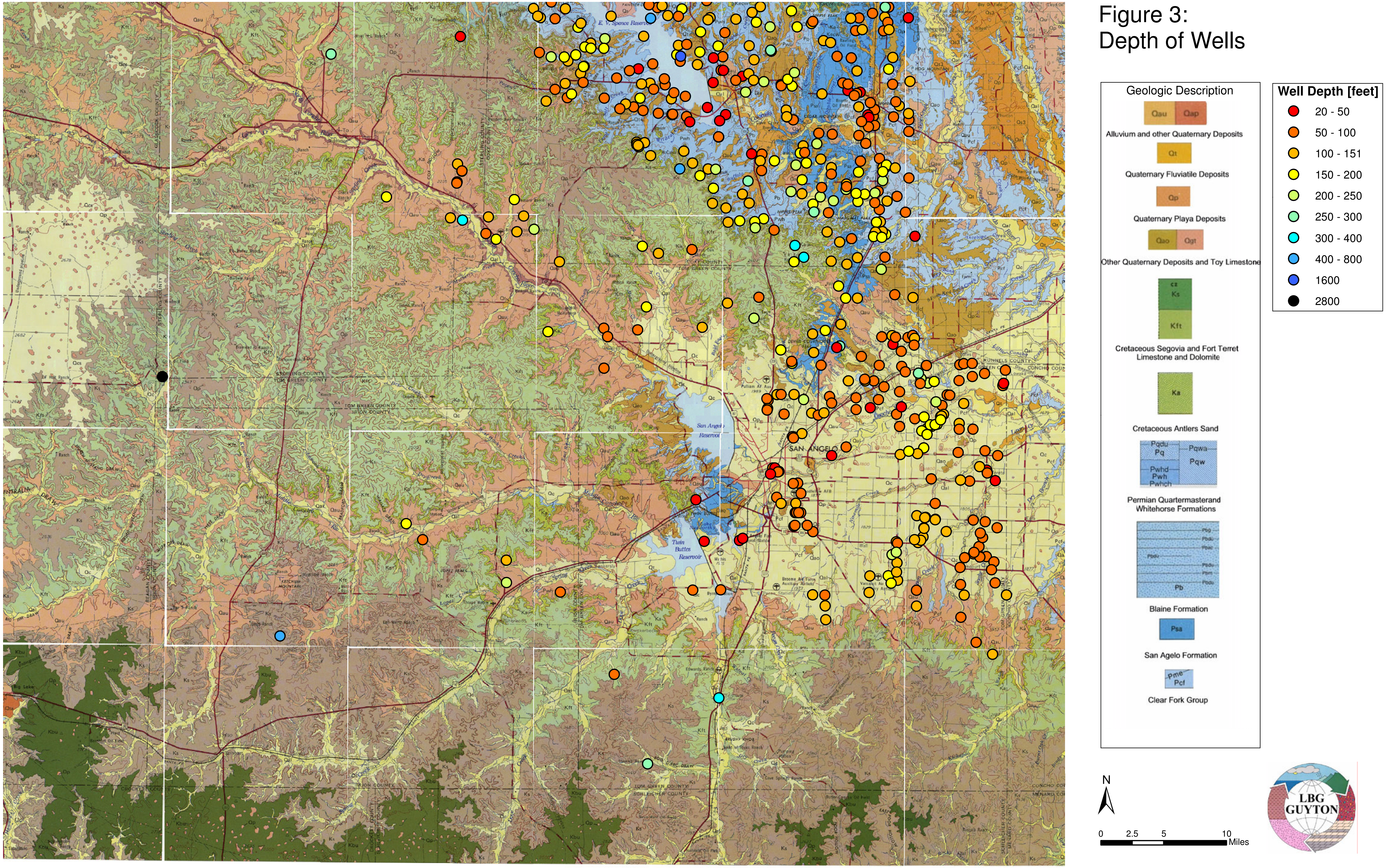


Figure 4: Water Quality

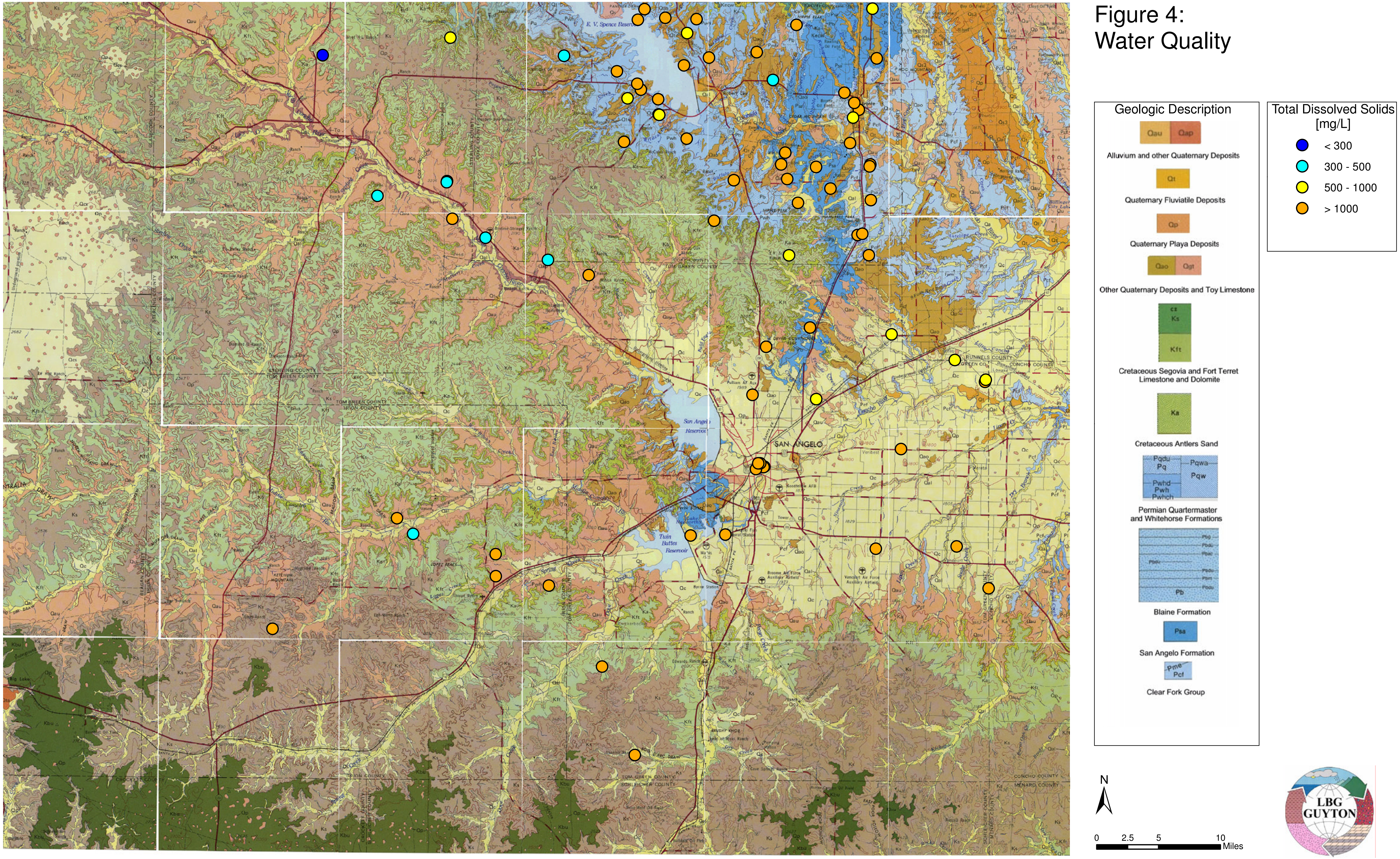
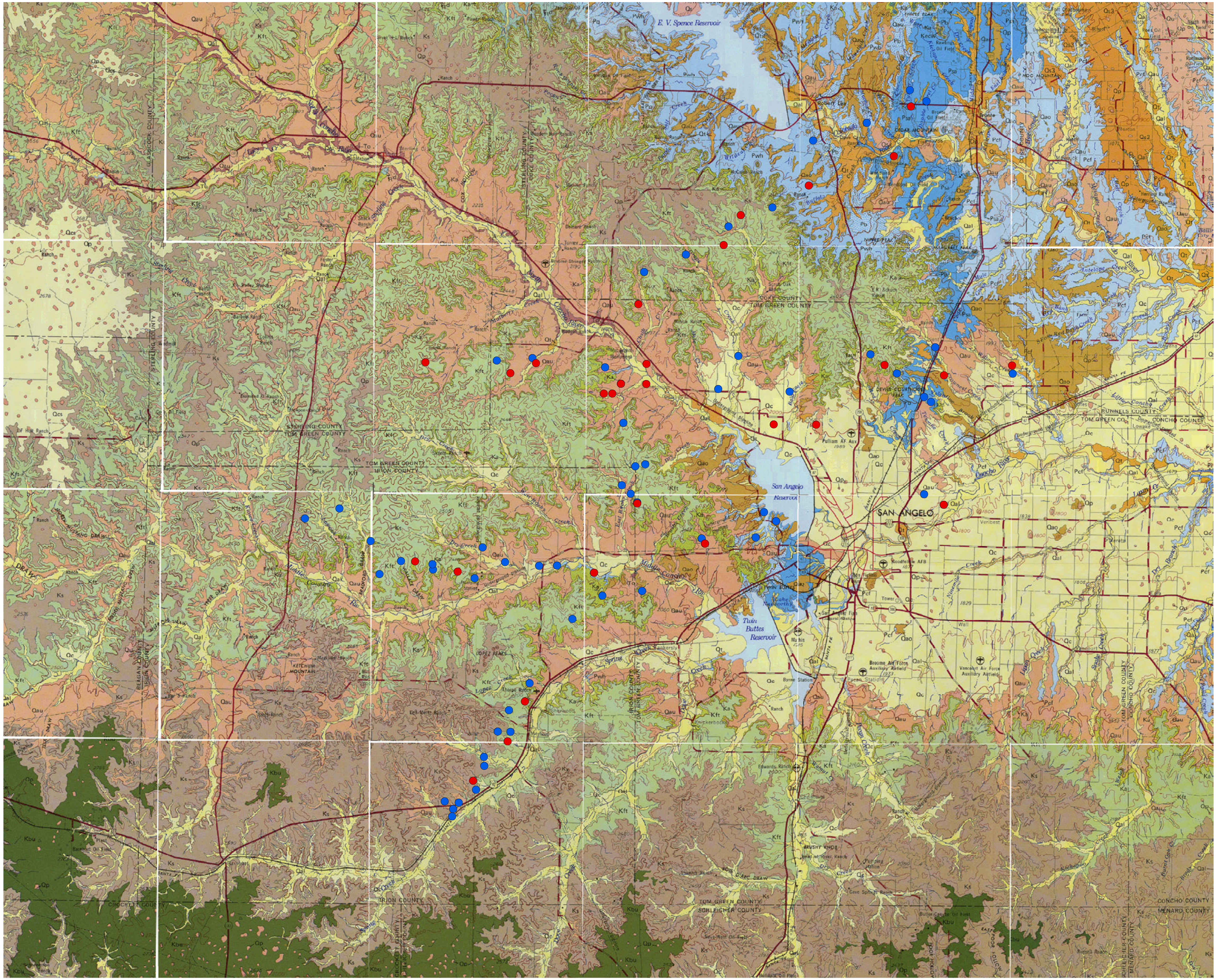


Figure 5: Location of Wells with Geophysical Logs



Well Data Source

- Texas Commission on Environmental Quality
- UT Bureau of Economic Geology

Geologic Description

Qau Qap — Alluvium and other Quaternary Deposits

Qt — Quaternary Fluviatile Deposits

Qp — Quaternary Playa Deposits

Qao Qpt — Other Quaternary Deposits and Toy Limestone

Ks Kft — Cretaceous Segovia and Fort Terret Limestone and Dolomite

Ka — Cretaceous Antlers Sand

Pqdu Pq Pqwa Pqw Pwhd Pwh Pwhch — Permian Quartermasterand Whitehorse Formations

Pb — Blaine Formation

Psa — San Agelo Formation

Pme Pcf — Clear Fork Group

0 2 4 8 Miles

N

3.1 Dockum Group

The Dockum Group of Triassic age consists of up to 2,000 feet of sands, silts, shales, and some gravels deposited in ancient structural Permian basins. Within the study area, the Dockum is first encountered in central Irion County and along the Sterling-Coke County line, thickens to approximately 200 feet along the western Irion and Sterling County lines, and continues to thicken in a northwesterly direction. The primary water-bearing zone in the Dockum Group is the Santa Rosa Formation, which consists of sand, silt, and conglomerate, with some layers of shale.

Very few wells produce from the Dockum in the study area, with only three wells in Irion County and seven in Sterling County being identified as producing from the Dockum in the TWDB database (Figure 1). There are likely more wells in existence that are completed in both the Dockum and the overlying Cretaceous units. Although well yields in excess of 1,000 gpm occur elsewhere in the aquifer's extent, the generally low permeability of the Dockum in the study area results in relatively low well yields locally. A TWDB test hole drilled near Sterling City found only minimal production from the Dockum. Water quality from groundwater in the Dockum is variable, but is generally poor. Fresh groundwater occurs in the shallower TWDB database wells, but is over 1,000 mg/L in the deeper wells.

3.2 Quartermaster Formation

The Quartermaster Formation is the uppermost Permian unit in the study area, and is located above the Whitehorse. This formation, which is equivalent to the Rustler Formation further to the west, consists of shale, siltstone, sandstone, gypsum, and dolomite, with a maximum thickness of 450 feet. Little is known about the use of the Quartermaster for water supply purposes. As shown in the cross section in Figure 2, this unit mainly occurs beneath the Cretaceous and Triassic units, and only outcrops in the study area in the far northern portions of the study area (Figure 1). As with the other Permian units in this study, it dips to the northwest towards the center of the Permian Basin.

3.3 Whitehorse Group

Formations comprising the Whitehorse Group lie below the Quartermaster Formation and Cretaceous units and consist of up to 700 feet of fine-grained red sand, dolomite, and thick gypsum beds. In places, the Whitehorse Group can be subdivided into the Yates, Seven Rivers, and Queen Formations *(the Grayburg Formation is included as a fourth formation in the TWDB Coke County Report 116)*. The Whitehorse crops out in a few small isolated locations in eastern Irion County and in a larger area surrounding and probably underlying Spence Reservoir. The Parks Well in south central Irion County appears to be completed in the upper portion of the Whitehorse. A few Whitehorse wells occur in Irion County, while numerous moderately shallow wells exist on the Whitehorse outcrop surrounding Spence Reservoir.

Well yields are small, generally less than 200 gpm, to moderate depending on the size and connectivity of fractures and cavities within the formation matrix. Some wells may initially appear to have large pumping capacities, but yields may dwindle as the groundwater held in storage in the immediate vicinity of the well becomes depleted. This was found to be the case with the Parks Well (see Section 4). Due to the nature of the aquifer, 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 aquifer varies greatly with generally moderately high concentrations of calcium, sulfate, and TDS. Fresh water may be encountered in the Whitehorse in recharge areas; however, this water rapidly deteriorates in quality in downdip portions of the aquifer. The moderately high TDS of water from the Parks Well (5,160 mg/L) is dominated by dissolved sulfate with a concentration of 2,400 mg/L. The high sulfate level is indicative of the dissolving of minerals in gypsum beds. See Section 4 for a more complete discussion on the dissolved constituents in groundwater from the Parks Well.

3.4 Pease River Group

The Blaine and San Angelo Formations of the Pease River Group are exposed at the land surface along a north-south, four to eight mile-wide band east of Robert Lee and west of San Angelo. In the subsurface, the formations dip westerly below the Whitehorse reaching a maximum thickness of about 1,500 feet.

Blaine - The Blaine Formation *(referred to as San Andres by Mear, 1963)* is composed of up to 1,200 feet of shale, sandstone, and beds of gypsum, halite, and anhydrite. Groundwater in the Blaine occurs in dissolution channels that have formed in the aquifer matrix.

Wells in the study area currently producing groundwater from the Blaine are primarily located in the outcrop area and generally produce low yields of shallow fresh to moderate saline water and saline water at deeper depths. The productivity of Blaine wells depends on the number and size of dissolution channels intersected by the well. Transmissivity, storage coefficient, and specific yield vary significantly, but are generally similar to those of the Whitehorse. 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.

The water quality from the Blaine aquifer varies greatly, but is generally slightly to moderately saline, and is dominated by calcium, magnesium, and sulfate ions. Total dissolved solids range from less than 1,000 to greater than 10,000 mg/L, although higher TDS groundwater is almost certainly found downdip and farther away from the outcrop. 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. 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 contamination of the aquifer by oil field brines.

San Angelo Sandstone – The San Angelo Sandstone formation is located stratigraphically below the Blaine Formation and consists of up to 250 feet of alternating beds of hard, bright red sandstone and conglomerate, with some shale. Wells completed in the San Angelo Sandstone usually produce less than 5 gpm, except for some wells in the vicinity of the Oak Creek Reservoir that produce 10 to 40 gpm (Wilson, 1973). Water in the San Angelo Sandstone is usually fresh to moderately saline, although groundwater with much higher TDS is found in the formation in the western portions of Coke County.

3.5 Clear Fork Group

The Clear Fork Group, which consists of the Choza, Vale, and Arroyo Formations, is 1,200 to 1,500 feet thick and produces fresh to slightly saline water to wells generally less than 200 feet deep. The Clear Fork outcrops along the eastern border of Coke County and extends into western Runnels County. In Tom Green County, the Clear Fork is overlain by Leona sand and gravel. Groundwater contained within the Leona and the hydrologically-connected upper portion of the Clear Fork constitutes the Lipan Aquifer.

The Choza Formation consists of up to 650 feet of grey, dolomitic limestone with some interbedded clay and silty clay. In Coke County the Choza is known to yield small to large quantities of mostly mineralized water to wells (Wilson, 1973). The Vale Formation consists of an upper massive dolomite, the Bullwagon Dolomite, which is up to 75 feet thick, followed by up to 140 feet of shale and sandy, gypsiferous shale. The Bullwagon can yield between 100 to 1,000 gpm to wells in Coke County. The remainder of the Vale is not known to yield water. The Arroyo Formation consists of an upper limestone member, the Standpipe Limestone, which is up to 15 feet of a light grey, marly limestone, which yields only small quantities of water to wells. The remainder of the Arroyo consists of up to 600 feet of alternating layers of shale and limestone, yielding small quantities of groundwater from the limestone horizons.

3.6 Wichita - Albany Group

The Wichita-Albany Group represents the deepest set of Permian-age formations in the study area. This relatively thick (approximately 1,300 feet) group of formations is exposed at the surface in central to eastern Concho County and extends northeastward into Runnels and Coleman Counties. The Wichita-Albany Group consists of eight formations beginning with the Lueders Formation at the top and culminating with the Coleman Junction at the base. The formations consist of limestone and shale, and generally yield only limited quantities of fresh to slightly saline groundwater near the outcrop and significantly more saline water at deeper depths.

Like all the other Permian formations, the Wichita-Albany Group dips underground in a west to northwesterly direction, and thus is encountered at great depths in the primary area of interest to this evaluation. The Coleman Junction is approximately 170 feet thick and is at a depth of approximately 3,400 feet underlying the Irion – Tom Green County border.

Groundwater leaking from the Coleman Junction has been detected in many abandoned oil wells, as many as 1,000 in Tom Green County alone (Richter and others, 1990). Water quality of the Coleman Junction is generally a hydrogen-sulfide brine and is highly corrosive with chloride concentrations approaching 30,000 mg/L.

4.0 PARKS WELL PUMPING TEST

Very little information is available on the hydrologic characteristics of the Permian aquifers in the study area. Therefore, as part of this study, a pumping test was conducted on the Parks Well, a flowing artesian well in the Whitehorse aquifer, located near the intersection of Highway 67 and FM 853 between San Angelo and Mertzon in Irion County (Figure 6). This well has an open-hole completion to a depth of 202 feet, and is cased to a reported depth of 175 feet.

4.1 Water Levels

The artesian pressure in the Parks Well was measured before testing on December 3, 2004 at an equivalent of 33.08 feet above ground surface, for a water level elevation of 2,190 feet AMSL (using the approximate land surface elevation of 2,157 feet AMSL in TWDB records). This water level is higher than most of the Permian outcrop to the north in Coke County and to the east in Tom Green County. However, this water level is similar to historical levels in wells completed in the Edwards and Trinity Groups to the west and south, which overlie the Permian subcrop. This may indicate a hydraulic connection from these areas to the Parks Well.

4.2 Transmissivity and Well Yield

A long-term flow test was conducted on the Parks Well on December 4, 2004. Additional monitoring wells included a stock well completed in the overlying Antlers Sand to a depth of 110 feet (MW-WINDMILL), a well completed to an unknown depth (MW-01), and a well reportedly completed in the Antlers Sand to a depth of 162 feet (MW-02). A site map is presented in Figure 6.

The Parks Well was fitted with an 8-inch propeller-style flowmeter to accurately measure discharge. Change in artesian pressure was measured with a direct-read pressure gauge and a pressure transducer with a recording device (Figure 7). A short 2-hour test was conducted on the afternoon of December 3rd and the well was allowed to recover

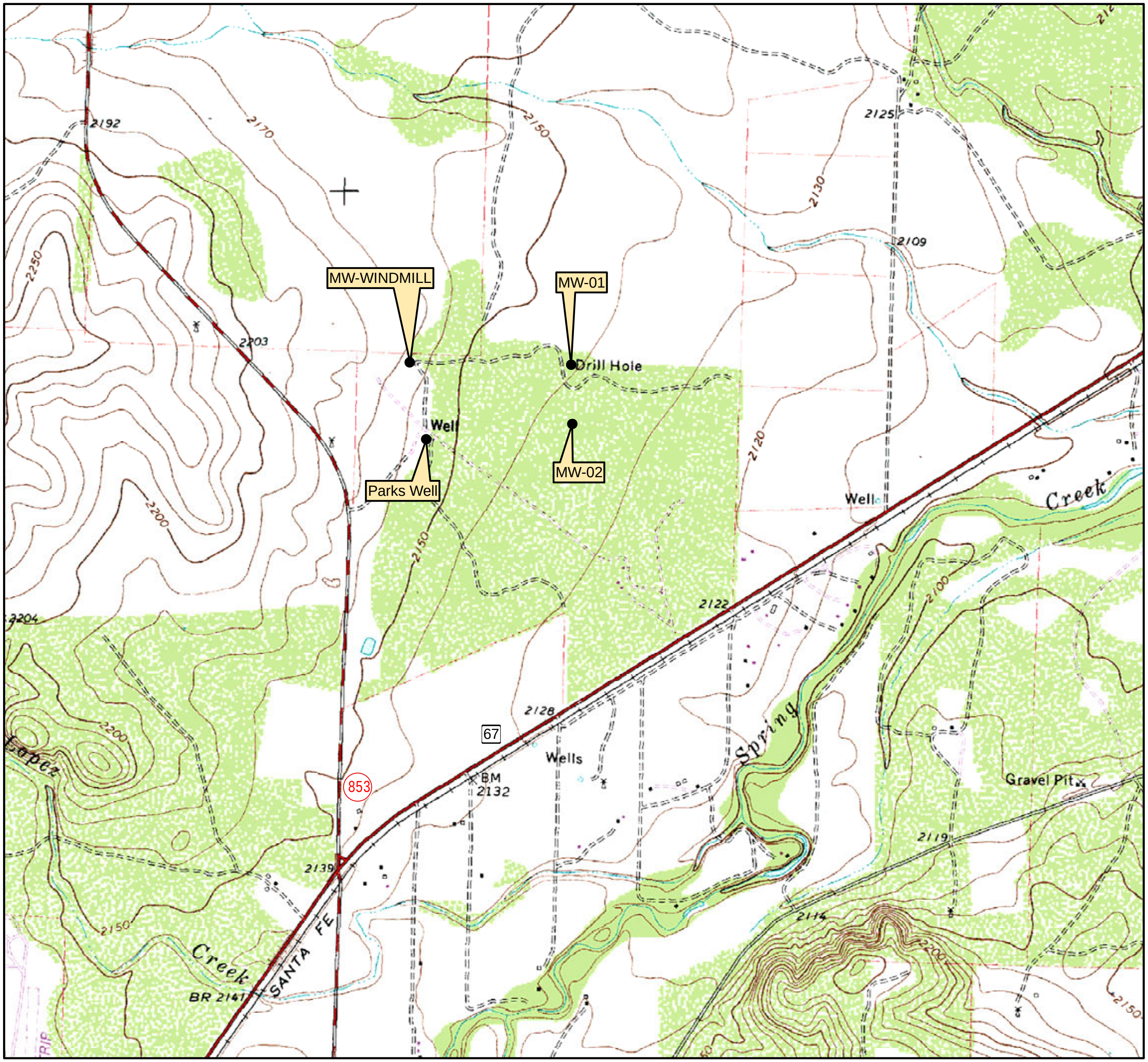


Figure 6:
Parks Wells

Figure 7: Photo of Parks Well

overnight. Prior to testing on December 3rd these gauges indicated an equivalent height of 28.08 feet above the gauges.

After an overnight recovery from the 2-hour test, the equivalent height of water above the pressure gauges was 25.81 feet before the long-term test. The test method used was a constant-drawdown method in which drawdown is kept constant and changes in flow are recorded. In the case of an artesian flow test the constant drawdown is the difference between the static artesian level and the point of discharge. In practice, the drawdown is somewhat less than this due to friction head loss. This changes with velocity, but the total change in friction loss over the analyzed portion of the test was less than 10% of total drawdown and should not be a significant source of error. The constant drawdown used for calculation purposes was 24.3 feet, which reflects the average effect of the head loss at the discharge.

The test began on the morning of December 4th and flow rates were measured at frequent intervals. The initial flow was 2,000 gpm. This flow steadily declined to a level of 388 gpm on the afternoon of December 5th. The test was stopped at this point due to concerns that the flowmeter would not accurately measure flows below about 350 gpm, and that the pressure gauges would begin to register atmospheric pressure and compromise complete collection of recovery data.

The test data was plotted on a semi-log chart and analyzed using the Jacob-Lohman method (Lohman, 1972). The results of this analysis are presented in Figure 8. This analysis indicates that a negative boundary is encountered beginning at approximately 100 minutes of flow. The most likely explanation for this is that the Parks Well is reportedly completed in a cavity, and this is responsible for the high transmissivity (82,400 gpd/ft) at the beginning of the test. Once this cavity and surrounding highly permeable zones are depleted, a lower-permeability matrix is encountered. The transmissivity of this lower-permeability material is represented by the second transmissivity calculation near the end of the test.

This second, long-term transmissivity is calculated to be 4,130 gpd/ft. Using this value and an estimated storativity of 10^{-4}, an estimated long-term specific capacity of 1.5 gpm/ft is obtained for the Parks Well. This well might be expected to produce 150 gpm on a consistent basis, with about 100 feet of drawdown. An accurate calculation of

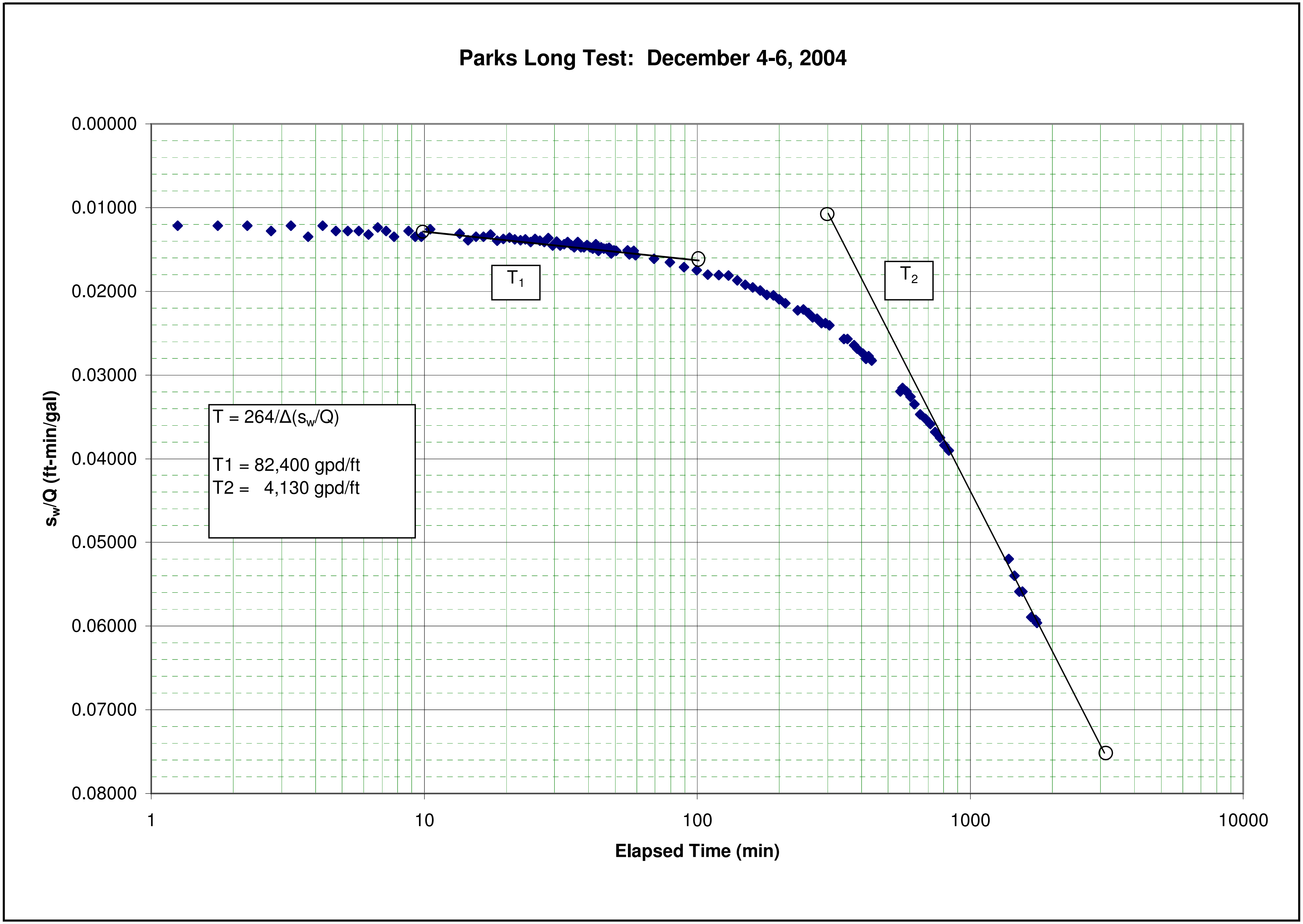


Figure 8: Semi-log Plot of Parks Well Pumping Test Results

storativity could not be performed due to uncertainty regarding the well radius in the open producing zone.

The water level in the nearby stock well (MW-WINDMILL) was measured at 52.02 feet below ground surface before testing on December 4th and did not change significantly during the test. There was an obstruction in MW-01 at a depth of 5 feet below the top of casing, which prevented accurate continuous level recording. MW-01 had standing water in the casing, which may have been due to artesian pressure, but no flow was observed from the casing. MW-02 was also apparently under slight artesian pressure, and a small trickle of flow was observed from the casing. The formation that MW-02 intercepts was reportedly plugged with cement during casing installation, and the water level in MW-02 may not accurately represent the level in the intercepted formation. Since the level measurement was controlled by the height of the casing outlet, no change in level was observed from this well. The small trickle of flow from MW-02 continued throughout the test.

The Parks Well was relatively slow to recover, recovering about 11 feet in 20 hours (Figure 9). This is probably due to the low permeability matrix indicated in the long-term flow test analysis.

4.3 Water Quality

Water chemistry samples were collected from the Parks Well on December 3rd. All reported analyte concentrations were below the respective primary drinking water Maximum Contaminant Levels (MCLs) where applicable. However, six analytes were not within the Texas secondary standards given in 30 TAC §290.105. These were Total Dissolved Solids (5,160 mg/L), chloride (920 mg/L), sulfate (2,400 mg/L), fluoride (2.46 mg/L), iron (0.304 mg/L), and field-measured pH (6.57). The water was also very hard, with a calcium and magnesium hardness of 2,330 mg/L as $CaCO_3$. The results of the December sampling are summarized in Table 1. Historical analytical results from samples collected from the Parks Well are presented in Table 2. These historical analytical results have been consistent over time for most constituents.

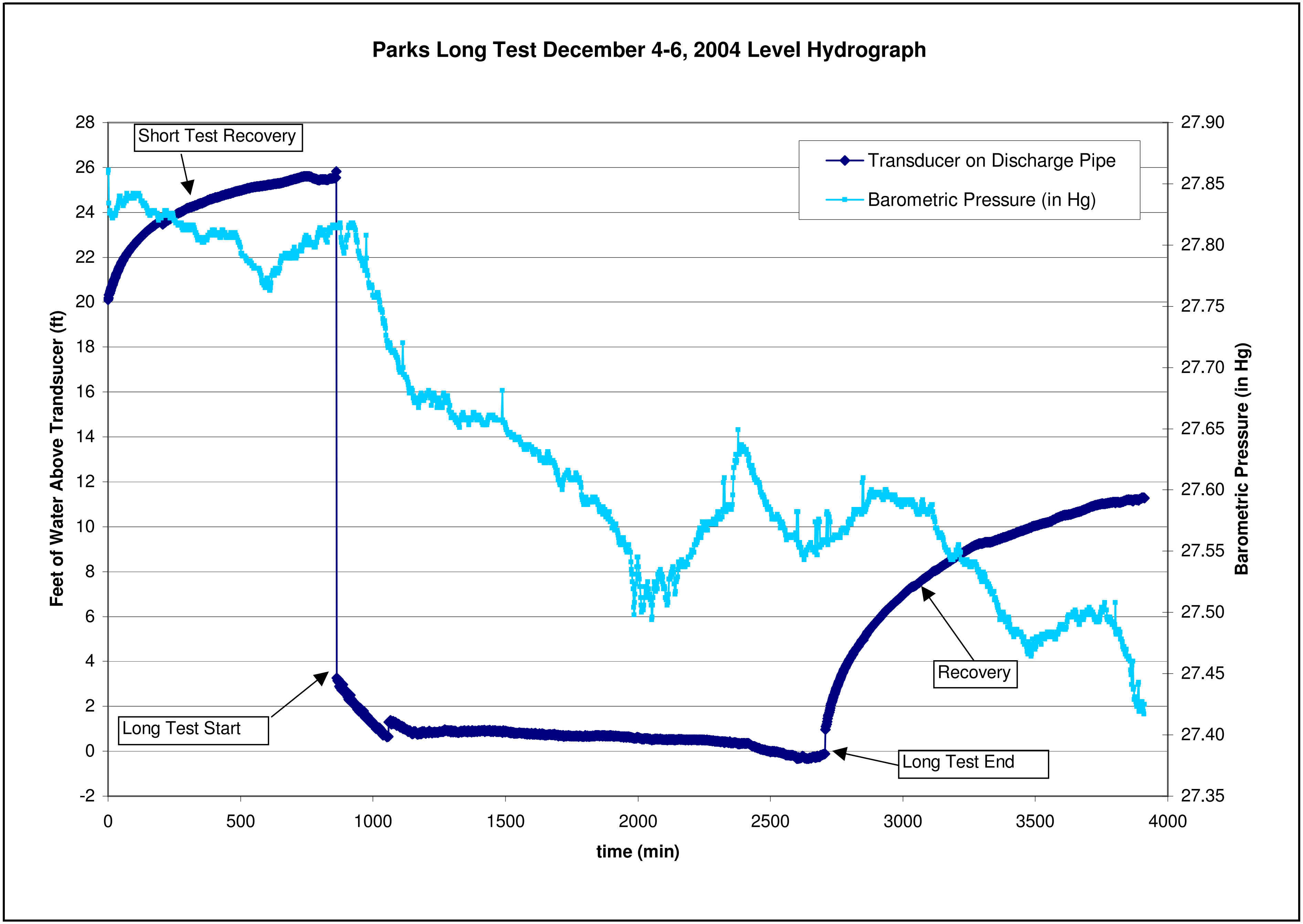


Figure 9: Water Level Hydrograph of Long Term Parks Well Test

Evaluation of the molar concentrations of major anions and cations in the Parks Well indicates that this saline water is a mixed Na-Ca (cation) and mixed Cl-SO_4 (anion) water. This composition indicates the solution of both gypsum and halite minerals in the aquifer matrix. The water appears to be slightly undersaturated with respect to these two minerals.

Table 1 Parks Well Water Quality Sampling Results, 12/3/04

Analyte	Primary (Secondary) MCL	Result	Units
Alkalinity, Bicarbonate (As CaCO3)	none	191	mg/L
Alkalinity, Total (As CaCO3)	none	191	mg/L
Arsenic	0.01	0.00225	mg/L
Bromide	none	2.24	mg/L
Cadmium	0.005	< 0.001	mg/L
Calcium	none	606	mg/L
Chloride	(300)	920	mg/L
Chromium	0.1	0.00306	mg/L
Copper	1.3 (1)	0.00318	mg/L
Fluoride	4.0 (2.0)	2.46	mg/L
Hardness, Calcium/Magnesium (As CaCO3)	none	2,330	mg/L
Iron	0.3	0.304	mg/L
Lead	0.015	< 0.001	mg/L
Magnesium	none	186	mg/L
Nitrogen, Nitrate and Nitrite	10	< 0.020	mg/L as N
pH, field	(>7)	6.57	
Potassium	none	22.8	mg/L
Selenium	0.05	< 0.004	mg/L
Silica, Dissolved (as SiO2)	none	14.6	mg/L
Sodium	none	671	mg/L
Sulfate	(300)	2,400	mg/L
Temperature, field	none	20.5	℃
Total Dissolved Solids	(1000)	5,160	mg/L

Table 2 Parks Well Historical Water Quality Sampling Results

Sample Date	Sulfate (mg/L)	Chloride (mg/L)	TDS (mg/L)	Calcium (mg/L)	Magnesium (mg/L)
11/10/60	2,290	851	4,741	610	201
08/07/67	2,271	883	4,810	640	190
08/13/79	2,369	882	4,882	634	181
05/17/85	2,381	872	4,933	634	189
12/03/04	2,400	920	5,160	606	186

5.0 CONCLUSIONS AND RECOMMENDATIONS

Westward dipping Permian-age formations are present in the study area that may produce varying quantities of fresh to saline quality groundwater to wells. Most existing water wells tapping these formations are less than 200 feet deep, were generally completed to supply only small quantities of water (i.e., stock wells), and thus do not provide conclusive information pertaining to the hydrological characteristics of these same geologic units where they occur at deeper depths. The numerous geophysical logs that are available in the area are useful in documenting the depth, thickness, and rock type characteristics at deeper depths, but do not provide yield or accurate water quality data. Recommendations provided in this report are thus developed based on a combination of hydrological characteristics observed at shallower depths and rock matrix characteristics determined from geophysical logs that suggest the potential for permeability development.

Most of the formations discussed in this report consist of limestone, shale, sandstone, and various forms of evaporites such as gypsum and anhydrite. Based on the formation descriptions, it appears that the most water productive zones are those that have developed where groundwater has dissolved passageways through the more susceptible rock types, primarily evaporite layers and fractured limestone beds. While evaporite layers are more susceptible to being dissolved by groundwater migrating through the subsurface, these environments also produce a groundwater that is high in TDS, particularly sulfates.

Three factors are critical in identifying a groundwater supply source for desalination: adequate sustainable well yield, reasonable water quality, and acceptable delivery distance to the desalination facility. At the current stage of evaluation, existing well data has not shown evidence that large quantities can be developed from the Triassic and Permian formations from a single well. The Parks Well test verified that initial large yields may decline as pumping continues over time. If further testing verifies this concern, it may require multiple moderate-yielding wells in combination to meet the total water supply needs of the project.

Water quality is an issue in regard to energy cost required to desalinate the brackish water. Groundwater with a TDS range of less than 5,000 mg/L is significantly less expensive to desalinate than water containing TDS on the order of 50,000 mg/L. And finally, pipeline cost also makes delivery distance an important consideration.

Based on these factors and known characteristics of the formations being considered, the following formations appear to have the best potential for development and should be further evaluated by drilling and constructing test wells in appropriate locations.

<u>The Whitehorse and Blaine Formations</u>: the full sections of the Whitehorse and Blaine Formations produces a favorable response on geophysical logs in the eastern portion of Irion County. Formation sample logs also indicate the presence of large sand and gypsum units in the Whitehorse and Blaine. The Whitehorse is known to produce moderate quantities of water from wells on the outcrop in southern Coke County. Geophysical logs indicate the full section of Whitehorse and Blaine extends to a depth of about 700 - 800 feet in eastern Irion County.

<u>The San Angelo Sandstone of the Pease River Group</u>: portions of this formation typically produce a favorable response on resistivity logs in the area west of San Angelo and can usually be reached within 550 feet in western Tom Green County, 800 feet in eastern Irion County, and 1,000 feet in northwestern Tom Green and southwestern Coke Counties.

<u>The Bullwagon Dolomite</u>: the Bullwagon Dolomite member of the Vale Formation is reported to have good production in shallow wells in Tom Green County, and typically produces a favorable response on resistivity logs in the area. The Bullwagon can be reached at about 1,300 feet depth in western Tom Green County and at about 1,500 feet in eastern Irion County, northwestern Tom Green County, and southwestern Coke County.

No significant supply from the Triassic-age Dockum within a reasonable distance was identified in this evaluation. Larger yields from the Dockum are known to exist elsewhere, however groundwater data in the local area was not encouraging. Likewise, the Coleman Junction Formation is not currently recommended based on its significant depth and corrosive, highly saline nature.

Figure 10 illustrates three areas in which initial evaluations were focused on specific geologic units. These locations allow for the full penetration of the entire formation thickness and are oriented slightly downdip of the formation outcrop such that maximum recharge potential is achieved.

Site 1 considers the Clear Fork Group formations and the Bullwagon Dolomite in particular. Test well depths at these locations would be approximately 900 to 1,000 feet.

Site 2 is positioned to best consider the Blaine and San Angelo Formations and, if desired, downdip extents of the Clear Fork formations. Depth to the Bullwagon Dolomite at these locations would be approximately 1,300 feet.

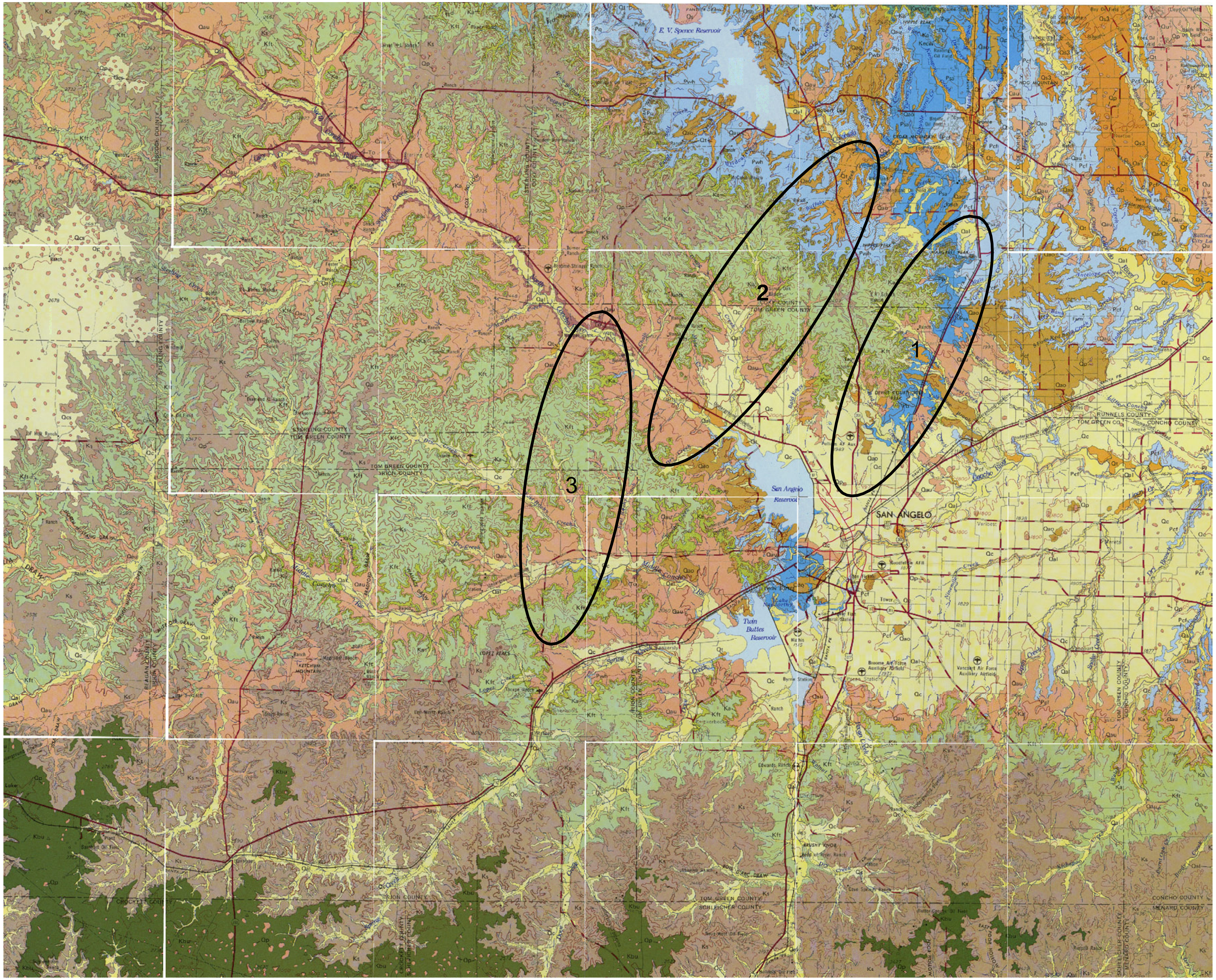
Site 3 is primarily intended to explore the full thickness of the Whitehorse and Blaine at depths of approximately 700 – 800 feet. Pease River formations would be reached at approximately 1,000 feet.

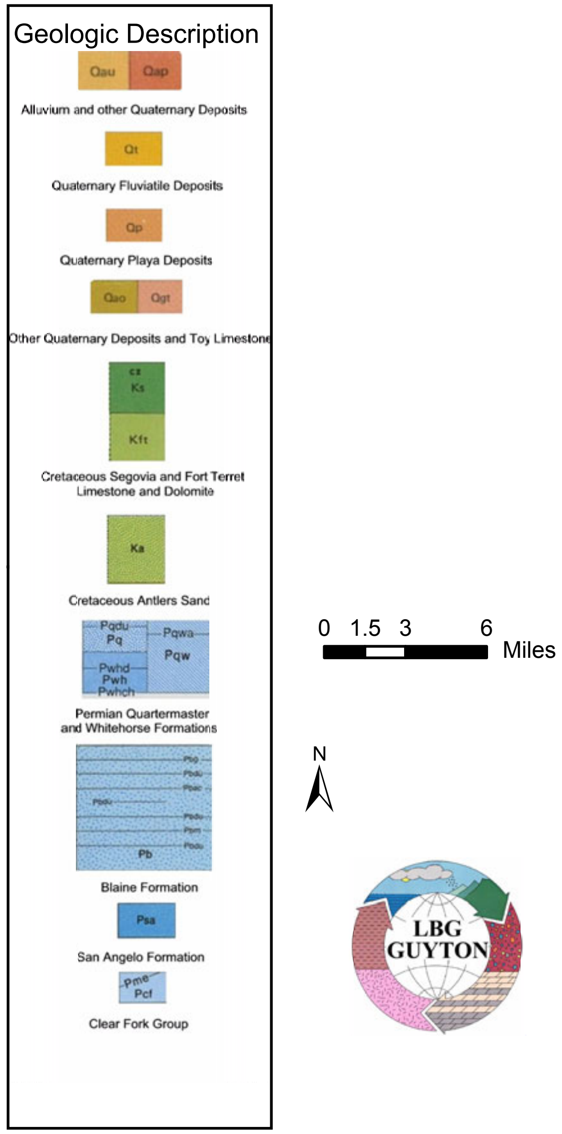
It is recommended that an initial investigation be conducted at Site 3 in the Whitehorse and Blaine Formations. Geophysical logs and formation sample logs indicate a promising amount of permeable sand and gypsum in this area. There is also very little competing use of the Whitehorse or Blaine in this area. This area is also far enough downdip of the outcrop of the Whitehorse to provide good potential elastic storage in the aquifer. Formations in Sites 1 and 2, although water bearing, appear to have less saturated thickness and permeability on the geophysical logs that are available in these areas.

Investigation should begin with a small diameter (8- to 10-inch) test hole through the Whitehorse and Blaine Formations at two locations within the area of Site 3 shown in Figure 10. The selection of two locations will provide information regarding the spatial distribution of aquifer properties that will be valuable in a future evaluation of water availability in the Whitehorse. Given the diverse nature of the formations that will be encountered, in most cases standard or air-assisted mud rotary drilling can be used for the test hole. A suite of borehole geophysical logging should be performed in the hole,

Figure 10: Suggested Test Hole Investigation Locations

Site	Investigation Zone
1	Clear Fork
2	Pease River and Clear Fork
3	Whitehorse and Blaine





including gamma, SP, long- and short-normal resistivity, and caliper. Formation samples should also be collected and accurately described, taking care to allow for uphole travel time in describing the sample interval.

If the initial test hole information suggests that the Whitehorse and Blaine may potentially produce a useful amount of groundwater, the hole can be reamed (to approximately 14 inches) and a test well may then be constructed to intercept the desired formation at appropriate intervals. Depending on the specific geologic setting, mud rotary, air, air reverse, or a combination of these drilling methods might be used for the reaming. A 6-inch submersible pump will likely be used to achieve the desired flow for testing (probably about 300 gpm), so the completed test wells should be at least 8 inches in diameter.

After test well construction and development, a test pump can be installed and a short series of step tests can be conducted, followed by a longer-term pumping test. Water quality samples should be collected near the end of the extended pumping period to assure that the sample analyses best characterize the true chemical quality of the aquifer. A small-diameter observation well should be drilled and constructed near the test well. This observation well will allow the maximum amount of information to be gathered during a subsequent long-term, constant-rate pumping test. Since little is known about water levels in the Whitehorse and Blaine in this area, the observation well might be constructed before or at the same time as the test well. Such a strategy might yield important water level and other information that can guide the design of the test well and pump.

A long-term, constant-rate test should last at least 72 hours, preferably longer, in order to evaluate the extent and sustainability of the aquifer. Care should be taken during testing not to allow any produced brackish water from the Whitehorse or Blaine to reach exposed recharge areas for the overlying Edwards/Trinity. The information collected during testing can be used to evaluate the potential production capacity of wells in the Whitehorse, and estimate the total volume of groundwater available to the wells on a long-term basis.

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Appendix C

Procedures for Test Holes and Test Wells

PROCEDURES FOR TEST HOLES AND TEST WELLS
San Angelo Desalination Project

Personnel

The drilling contractor will typically provide a two- to four-man drilling crew and this crew will be present on the site during all phases of the work. A professional engineer or geologist from LBG-Guyton Associates will also be on site for much of the drilling, construction, and testing. Trucks delivering drilling and well construction materials will also come to the site on a regular basis. Occasionally other persons involved with the project (representatives of UCRA, City of San Angelo, LBG-Guyton Associates, Freese & Nichols, the Irion County Water Conservation District, or the Texas Water Development Board) may visit the site.

Equipment

The drilling and testing program will generally involve the following types of equipment: a large drilling rig, a construction trailer, a pipe trailer, a mud pump, tanks for water and mud storage, a pit for cutting storage, a backhoe, air compressors, portable lights, and generators. Drilling contractors normally generate their own electric power. If there is a good source of water on the property for use in the drilling operation, the drilling contractor will likely want to use it; otherwise the water will be trucked in.

Hours

Many drilling contractors prefer to work day and night in two 12-hour shifts to save time and take advantage of cooler conditions at night. Daytime-only shifts are usually from 6 am to 6 pm.

Phase I - Test Holes

1. In the first phase of the project, test holes will be drilled to find a feasible test well location. It is not likely that more than three test holes on a particular property will be required for this purpose. Test hole locations will generally be chosen according to expected geologic conditions, elevation, and ease of access. It is anticipated that suitable locations will be found near established roads on the property, but a short road to the test site(s) may be required and will be built by the contractor.

2. It is expected that mud rotary drilling will be used for the test holes to account for varying geologic conditions and to provide good formation samples. The mud rotary drilling fluid (bentonite clay) is usually contained within pits or steel tanks. Sand, rock, and clay borehole cuttings are usually deposited in pits on the site, and graded level at the completion of the project. After completion of the project, drilling mud is often used to line tanks or ponds on the property, or hauled off the property. Formation water and cuttings will be similarly contained if other types of drilling are used. Depending on the geologic conditions encountered or the type of drilling used, it may be necessary to set surface casing in each test hole.

3. When the total depth of the test hole is reached (less than 1,000 ft) a geophysical logging suite will be run in the hole.

4. A small-diameter screen or slotted casing and blank casing will be installed in the test hole and will be cemented to the base of the formation above the Whitehorse aquifer. The drilling fluid will be removed from the hole by airlift pumping. Continuing to airlift pump the formation after the drilling mud has been removed will give an indication of the productiveness of the aquifer in the test location and the quality of the water. If both quantity and quality of the water indicate a promising site for a test well the second phase will begin with a test well being constructed about 1,000 ft from the test hole.

5. If the preliminary estimate of quantity or quality obtained from the test hole pumping is not appropriate for desalination, another test hole site on the property may be chosen. If no test well is completed at a site, the test hole will be plugged according to state standards by filling with cement.

Phase II - Test Well

1. If the test hole of Phase I indicates a promising location for a test well, a test well will be constructed within 1,000 ft of the test hole. The original test hole at the site will be used as an observation well during the testing.

2. A small diameter pilot hole for the test well will be drilled and logged in a fashion similar to the test hole.

3. The hole will be reamed to a larger diameter and a test well will be constructed. The test well will be of a gravel-pack construction screened in the Whitehorse aquifer. LBG-Guyton Associates will determine the screen size and intervals based on analysis of the geophysical logs and lithologic samples. The well casing will be pressure cemented from the top of the Whitehorse aquifer to the surface.

4. The well will be developed to improve production over a period of two or three days.

5. A 36- to 72-hour pumping test will be conducted to assess the productive capacity of the well and formation. The well completed in the original test hole will be used as an observation well. Drilling personnel and LBG-Guyton will be on site for the duration of the test. Any brackish water produced during the development period and during the pumping test will be kept from Edwards-Trinity recharge areas.

6. After completion of testing the pump will be removed and the two wells will be capped for possible future use. If the wells are not used in future production or testing, then the wells will be properly plugged with cement or other approved material.

Appendix D

Opinions of Probable Cost and Sensitivity Analysis for Brackish Groundwater Desalination Facilities

Appendix D: Opinions of Probable Cost and Sensitivity Analysis for Brackish Groundwater Desalination Facilities

Basis for Cost Estimates

Cost estimates for proposed facilities are based on a conceptual design for a desalination facility located on the west or northwest side of the city of San Angelo. The conceptual design uses the following assumptions:

- An initial production capacity of 5 MGD, expandable to 10 MGD.
- A production well field with 28 wells at ultimate capacity, with a well spacing of approximately 1 well per square mile. The actual number of wells and well spacing may change as more information becomes available regarding the hydrogeology of the aquifer.
- A ground storage tank and a pump station at a central location in the well field. The storage facilities will provide about 6 hours of storage at maximum capacity. The pump stations will be designed for an ultimate capacity of 12.5 MGD.
- A 12-mile 30-inch pipeline from the pump station to the treatment facility. The length of the pipeline may vary depending upon the final sites of the well field pump station and treatment facility.
- A treatment facility including a 5,000 square-foot metal building, reverse osmosis membrane, disinfection facilities, and storage for up to 12 hours of water production.
- A 0.5-mile 16-inch pipeline to carry brine reject from the treatment plant to the disposal facilities. The conceptual design assumes that the disposal facilities will be located very near the treatment plant. If potential co-disposal opportunities prove feasible and cost-effective, the transmission facilities may be different.
- Brine lagoons with up to 15 days of storage at the disposal site. Evaporation from the lagoons will somewhat reduce the volume of brine for disposal.
- Up to 12 disposal wells. The number of disposal wells may vary depending upon site-specific characteristics of the receiving formation.

Cost estimates for reverse osmosis treatment are based on information provided by equipment vendors. Other estimates are based on experience for similar facilities designed by Freese and Nichols, Inc. and LBG-Guyton Associates.

Well Construction and Development Criteria

Brackish source water wells should meet Texas standards for public supply wells as described in 30 TAC §290.41(c). In addition to these requirements, surface casing shall extend completely through any fresh water aquifers above the brackish producing intervals. In cases where the brackish producing interval is not competent for an open-hole completion, Type 304 stainless steel well screen and blank shall be used. Steel API line pipe may be used for surface casing in test wells, provided dielectric couplings are used to join dissimilar metals where necessary. Subsequent brackish production wells should use Type 304 stainless steel surface casing.

After a well is constructed, it shall be developed by agitation methods such as pumping with air or other means and then with a test pump. The development shall continue until the well is thoroughly cleaned and the water produced is clear. The well shall be cleaned out to its total depth before the test pump is installed.

Freese and Nichols

Simon W. Freese, P.E. 1900-1990
Marvin C. Nichols, P.E. 1896-1969

Title: Upper Colorado River Authority
City of San Angelo - 10.0 MGD Brackish Water Treatment Plant Phased Approach
Phase 1 - Initial 5.0 MGD Treatment Plant

Date: Sep. 16, 2005
By: ICA
Chkd: DWS

	QTY	UNIT	UNIT PRICE	TOTAL
Capital Cost				
Well Site				
Land Acquisition	168	ac	$ 2,000.00	$ 336,000.00
Well Pumps (10-500 gpm)	14	ea.	$ 15,000.00	$ 210,000.00
Well Collection Piping (8-inch pipe)	14,000	L.F.	$ 20.00	$ 280,000.00
Well Construction	14	ea.	$ 140,000.00	$ 1,960,000.00
Ground Storage Tank (1.5 MG - 5.8 hr. @ 6.25 MGD)	1	L.S.	$ 500,000.00	$ 500,000.00
Pumps from GST to Treatment Plant (2-4000 gpm)	2	ea.	$ 70,000.00	$ 140,000.00
Total Well				$ 3,426,000.00
Treatment Equipment				
Land Acquisition	30	ac	$ 2,000.00	$ 60,000.00
Reverse Osmosis (5.0 MGD Plant)	1	L.S.	$ 2,625,000.00	$ 2,625,000.00
Ground Storage Tank (2.5 MG - 12 hrs @ 5.0 MGD)	1	L.S.	$ 750,000.00	$ 750,000.00
Disinfection Facility (Chlorinators for 5.0 MGD)	1	L.S.	$ 120,000.00	$ 120,000.00
Total Treatment Equipment				$ 3,555,000.00
Reject Facilities				
High Pressure Membrane Reject				
19 MG Brine Lagoon @ Plant Site (15 days storage @ 5.0 MGD (11.5	1	L.S.	$ 1,350,000.00	$ 1,350,000.00
High Pressure Well Disposal Pumps (2-1300 gpm)	2	ea.	$ 20,000.00	$ 40,000.00
Disposal Wells	6	ea.	$ 1,000,000.00	$ 6,000,000.00
Total Reject Facilities				$ 7,390,000.00
Pipeline (Transmission)				
16" Dia. Pipeline (2300 gpm to disposal site(1157 initially @ 5.0 MGD))	2,000	L.F.	$ 37.00	$ 74,000.00
30" Dia. Pipeline (6.75 MGD from Wells to Treatment Plant)	65,000	L.F.	$ 86.00	$ 5,590,000.00
Easement	46.14	acre	$ 1,000.00	$ 46,143.07
Total Pipeline (Transmission)				$ 5,710,143.07
Building				
Metal Building	5,000	S.F.	$ 90.00	$ 450,000.00
Total Building				$ 450,000.00
Electrical				
Total Electrical: 15% of Equipment Cost				$ 352,800.00
Instrumentation				
Total Instrumentation: 10% of Equipment Cost				$ 235,200.00
Power Service				
Total Power Service	10,000	L.F.	$ 30.00	$ 300,000.00

Subtotal	$ 21,420,000.00
Contingency (17.4%)	$ 3,728,000.00
TOTAL CONSTRUCTION COST	**$ 25,148,000.00**
Engineering & Construction Services (15%)	$ 3,773,000.00
TOTAL CAPITAL COST	**$ 28,921,000.00**

Freese and Nichols

Simon W. Freese, P.E. 1900-1990
Marvin C. Nichols, P.E. 1896-1969

Title: Upper Colorado River Authority
City of San Angelo - 10.0 MGD Brackish Water Treatment Plant Phased Approach
Phase 1 - Initial 5.0 MGD Treatment Plant

Date: Sep. 16, 2005
By: ICA
Chkd: DWS

	QTY	UNIT	UNIT PRICE	TOTAL
Treatment				
RO				
power consumption (kw-hr/ gal)	5,000,000	gal/day	$0.160 / 1000 gal	$ 292,000.00
membrane replacement	5,000,000	gal/day	$0.050 / 1000 gal	$ 91,250.00
cartridge filters	5,000,000	gal/day	$0.020 / 1000 gal	$ 36,500.00
chemicals ($ / gal)	5,000,000	gal/day	$0.220 / 1000 gal	$ 401,500.00
Disinfection				
chemicals ($ / gal)	5,000,000	gal/day	$0.009 / 1000 gal	$ 16,060.00
Total Treatment				$ 837,310.00
Labor				
1 employee (40 hours per week)	2,080	Hrs.	$ 24.00	$ 49,920.00
Total Labor				$ 49,920.00
Pumping (Transmission)				
Pumping from wells to GST (power cost)	3,490,744	kw-hr	$0.06 / kw-hr	$ 209,444.66
Pumping from GST to Treatment Plant (power cost)	140,321	kw-hr	$0.06 / kw-hr	$ 8,419.24
Pumping into disposal well (power cost)	2,867,397	kw-hr	$0.06 / kw-hr	$ 172,043.83
Total Pumping (Transmission)				$ 389,907.73
Annual Maintenance				
Total Annual Maintenance (5% of Equipment Cost)				$ 117,600.00
			Subtotal	$ 1,395,000.00
			Contingency (10%)	$ 140,000.00
			TOTAL ANNUAL OPERATION AND MAINTENANCE COST	**$ 1,535,000.00**

Freese and Nichols

Simon W. Freese, P.E. 1900-1990
Marvin C. Nichols, P.E. 1896-1969

Title: Upper Colorado River Authority
City of San Angelo - 10.0 MGD Brackish Water Treatment Plant Phased Approach
Phase 2 - Upgrade to a 10.0 MGD Treatment Plant

Date: Sep. 16, 2005
By: ICA
Chkd: DWS

	QTY	UNIT	UNIT PRICE	TOTAL
Well Site				
Land Acquisition	168	ac	$ 2,000.00	$ 336,000.00
Well Pumps (10 additional 500 gpm pumps)	14	ea.	$ 15,000.00	$ 210,000.00
Well Collection Piping (8-inch pipe)	14,000	L.F.	$ 20.00	$ 280,000.00
Well Construction (Additional wells)	14	ea.	$ 140,000.00	$ 1,960,000.00
Ground Storage Tank (1.5 MG - 5.8 hr. @ 6.25 MGD)	1	L.S.	$ 500,000.00	$ 500,000.00
Pumps from GST to Treatment Plant (3 additional 4000 gpm pumps)	3	ea.	$ 70,000.00	$ 210,000.00
Total Well				$ 3,496,000.00
Treatment Equipment				
Reverse Osmosis (Additional 5.0 MGD to existing Plant)	1	L.S.	$ 2,625,000.00	$ 2,625,000.00
Disinfection Facility (Additional Chlorinators)	1	L.S.	$ 50,000.00	$ 50,000.00
Total Treatment Equipment				$ 2,675,000.00
Reject Facilities				
High Pressure Membrane Reject				
19 MG Brine Lagoon @ Plant Site (15 days storage @ 5.0 MGD (11.5	1	L.S.	$ 1,350,000.00	$ 1,350,000.00
High Pressure Well Disposal Pumps (1 additional 1300 gpm pump)	1	ea.	$ 20,000.00	$ 20,000.00
Disposal Wells (Additional)	6	ea.	$ 1,000,000.00	$ 6,000,000.00
Total Reject Facilities				$ 7,370,000.00
Electrical				
Total Electrical: 15% of Equipment Cost				$ 357,525.00
Instrumentation				
Total Instrumentation: 10% of Equipment Cost				$ 238,350.00

Subtotal	$ 14,137,000.00
Contingency (17.4%)	$ 2,460,000.00
TOTAL CONSTRUCTION COST	**$ 16,597,000.00**
Engineering & Construction Services (15%)	$ 2,490,000.00
TOTAL CAPITAL COST	**$ 19,087,000.00**

Simon W. Freese, P.E. 1900-1990
Marvin C. Nichols, P.E. 1896-1969

Title: Upper Colorado River Authority	**Date:** Sep. 16, 2005
City of San Angelo - 10.0 MGD Brackish Water Treatment Plant Phased Approach	**By:** ICA
Phase 2 - Upgrade to a 10.0 MGD Treatment Plant	**Chkd:** DWS

	QTY	UNIT	UNIT PRICE	TOTAL
Treatment				
RO				
power consumption (kw-hr/ gal)	10,000,000	gal/day	$0.160 / 1000 gal	$ 584,000.00
membrane replacement	10,000,000	gal/day	$0.050 / 1000 gal	$ 182,500.00
cartridge filters	10,000,000	gal/day	$0.020 / 1000 gal	$ 73,000.00
chemicals ($ / gal)	10,000,000	gal/day	$0.220 / 1000 gal	$ 803,000.00
Disinfection				
chemicals ($ / gal)	10,000,000	gal/day	$0.009 / 1000 gal	$ 32,120.00
Total Treatment				$ 1,674,620.00
Labor				
1 employee (40 hours per week)	2,080	Hrs.	$ 24.00	$ 49,920.00
Total Labor				$ 49,920.00
Pumping (Transmission)				
Pumping from wells to GST (power cost)	6,981,489	kw-hr	$0.06 / kw-hr	$ 418,889.33
Pumping from GST to Treatment Plant (power cost)	954,180	kw-hr	$0.06 / kw-hr	$ 57,250.80
Pumping into disposal well (power cost)	5,734,794	kw-hr	$0.06 / kw-hr	$ 344,087.66
Total Pumping (Transmission)				$ 820,227.79
Annual Maintenance				
Total Annual Maintenance (5% of Equipment Cost)				$ 119,175.00
			Subtotal	$ 2,664,000.00
			Contingency (10%)	$ 267,000.00
			TOTAL ANNUAL OPERATION AND MAINTENANCE COST	**$ 2,931,000.00**

UCRA/San Angelo Groundwater Desalination
Probable Cost Sensitivity Analysis

9/16/2005

Variable Factors

		Low $	Trial	High $		Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	Trial 8
Land Req'd per well		**12**	12	**290**	acres	12	50	50	50	50	50	50	50
Well Spacing		**1000**	1000	**5000**	feet	1000	2000	2000	2000	2000	2000	2000	2000
Well Capacity		**350**	350	**200**	gpm	350	300	**200**	300	300	300	300	300
No. Production Wells	calc.	**12.4**	13.2	**26.7**		13.2	15.4	23.1	15.4	15.4	15.4	17.8	15.4
	actual		14			14	16	24	16	16	16	18	16
Well Cost		**140,000**	140,000	**200,000**	$/well	140,000	150,000	150,000	150,000	150,000	150,000	150,000	150,000
Transmission Distance		**65,000**	65,000	**120,000**	feet	65,000	80,000	80,000	80,000	**120,000**	80,000	80,000	80,000
RO Recovery		**80%**	75%	**65%**		75%	75%	75%	75%	75%	75%	**65%**	75%
Required Production	5 MGD	**4340**	4630	**5342**	gpm	4630	4630	4630	4630	4630	4630	5342	4630
Waste Generated	5 MGD	**868**	1157	**1870**	gpm	1157	1157	1157	1157	1157	1157	1870	1157
Disposal Well Capacity		**200**	200	**70**	gpm	200	175	175	**125**	175	175	175	175
No. Disposal Wells	calc.	**4.3**	5.8	**26.7**		5.8	6.6	6.6	9.3	6.6	6.6	10.7	6.6
	actual		6			6	7	7	10	7	7	11	7
Disposal Well Spacing		**500**	500	**1000**	feet	500	700	700	700	700	700	700	**1000**
Disposal Well Cost		**800,000**	1,000,000	**1,500,000**	$/well	1,000,000	1,200,000	1,200,000	1,200,000	1,200,000	1,200,000	1,200,000	**1,500,000**
Land Req'd per well		**0.7**	1	**18**	acres	1	3	3	3	3	1	1	**10**
Power Cost		**$ 0.06**	0.06	**$ 0.10**	/kW-hr	0.06	0.075	0.075	0.075	0.075	**0.09**	0.07	0.075
Contingency		**15%**	17.4%	**35%**		17.4%	25.0%	25.0%	25.0%	25.0%	25.0%	25.0%	25.0%
Utilization		**100%**	100%	**25%**		100%	100%	100%	100%	100%	100%	100%	100%
Interest		**4%**	6%	**6%**		6%	6%	6%	6%	6%	6%	6%	6%
Loan Period		**30**	20	**20**	years	20	20	20	20	20	20	20	20

		Trial	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	Trial 8
Capital Cost, 5 MGD		$ 28,921,000	$28,921,000	$39,127,000	$42,656,000	$44,302,000	$44,111,000	$39,127,000	$46,908,000	$ 42,146,000
10 MGD		$ 48,008,000	$48,008,000	$65,916,000	$72,974,000	$76,266,000	$70,900,000	$65,916,000	$81,480,000	$ 71,953,000
O&M Cost 5 MGD		$ 1,535,000	$ 1,535,000	$ 1,643,000	$ 1,646,000	$ 1,643,000	$ 1,643,000	$ 1,751,000	$ 1,787,000	$ 1,643,000
10 MGD		$ 2,931,000	$ 2,931,000	$ 3,176,000	$ 3,179,000	$ 3,176,000	$ 3,225,000	$ 3,405,000	$ 3,469,000	$ 3,176,000
Unit Cost $/1000 gal.										
	Debt Service	$ 1.38	$ 1.38	$ 1.87	$ 2.04	$ 2.12	$ 2.11	$ 1.87	$ 2.24	$ 2.01
	O&M	$ 0.84	$ 0.84	$ 0.90	$ 0.90	$ 0.90	$ 0.90	$ 0.96	$ 0.98	$ 0.90
5 MGD	Total	$ 2.22	**$ 2.22**	**$ 2.77**	**$ 2.94**	**$ 3.02**	**$ 3.01**	**$ 2.83**	**$ 3.22**	**$ 2.91**
	Debt Service	$ 1.15	$ 1.15	$ 1.57	$ 1.74	$ 1.82	$ 1.69	$ 1.57	$ 1.95	$ 1.72
	O&M	$ 0.80	$ 0.80	$ 0.87	$ 0.87	$ 0.87	$ 0.88	$ 0.93	$ 0.95	$ 0.87
10 MGD	Total	$ 1.95	**$ 1.95**	**$ 2.44**	**$ 2.61**	**$ 2.69**	**$ 2.58**	**$ 2.51**	**$ 2.90**	**$ 2.59**

Appendix E
Response to Texas Water Development Board Comments

Appendix E: Response to Texas Water Development Board Comments

1. The scope of work included in this report (page 1-8) is not the scope of work contracted under TWDB Contract No. 2004-483-525 and the report appears to not address some of the TWDB scope of work items. Specifically, it appears that the following SOW items have not been addressed. Please clarify how the tasks were met:

   - Wellfield location and well spacing information

     The approximate location of the well field may be found in Figure 5-1 and Area 3 of Figure 2-5 and Figure 10 in Appendix B. More specific information about well field location will not be available until arrangements have been made with landowners in the area. An introduction to Appendix D has been added with a description of the assumptions used to develop cost estimates for the project, including assumptions about well spacing.

   - Well completion and development criteria

     Well completion and development criteria have been added to the introduction to Appendix D.

   - Well Field infrastructure needs

     A brief description of well field infrastructure needs may be found in Chapter 5. Additional descriptive information has been added to Appendix D.

   - Description of screening process used in alternative selection.

     Section 2.4 has been reorganized to make the screening process used to evaluate sources more apparent to the reader. The process used for selecting brackish water sources is described in Appendix B. Please note that these are not the only alternatives available to San Angelo. It was not within our scope of work for this project to evaluate all alternatives.

   - Methodology utilized to develop costs.

     A description of the methodology used to develop cost estimates has been added to Appendix D.

2. Please clarify information found in the tables in Appendix D and address whether or not this data addresses scope of work requirements, if applicable.

   Additional clarifying text has been added to Appendix D. Other information may be found in Appendix B.

3. The titles of Tables 4-2, 4-3 and, 4-4 all have the same phrase “San Angelo Sandstone” in their titles but seem to concern different formations. In addition the text references different formations than that referenced in the title. Page 4-7 refers to Table 4-3 as the Clear Fork

Group, and Page 4-11 refers to Table 4-4 as the Wolfcamp formation. Also 11 of the 12 entries in Tables 4-2 and 4-3 are duplicated. Please review and revise as appropriate.

Tables have been updated.

4. The titles of Figures 2-1, 2-2, and 5-4 as they appear in the List of Figures differ from the titles of the actual figures found on pages 2-2, 2-5, and 5-4 respectively. Please review and revise as appropriate.

    The Table of Contents has been corrected to match the figures.