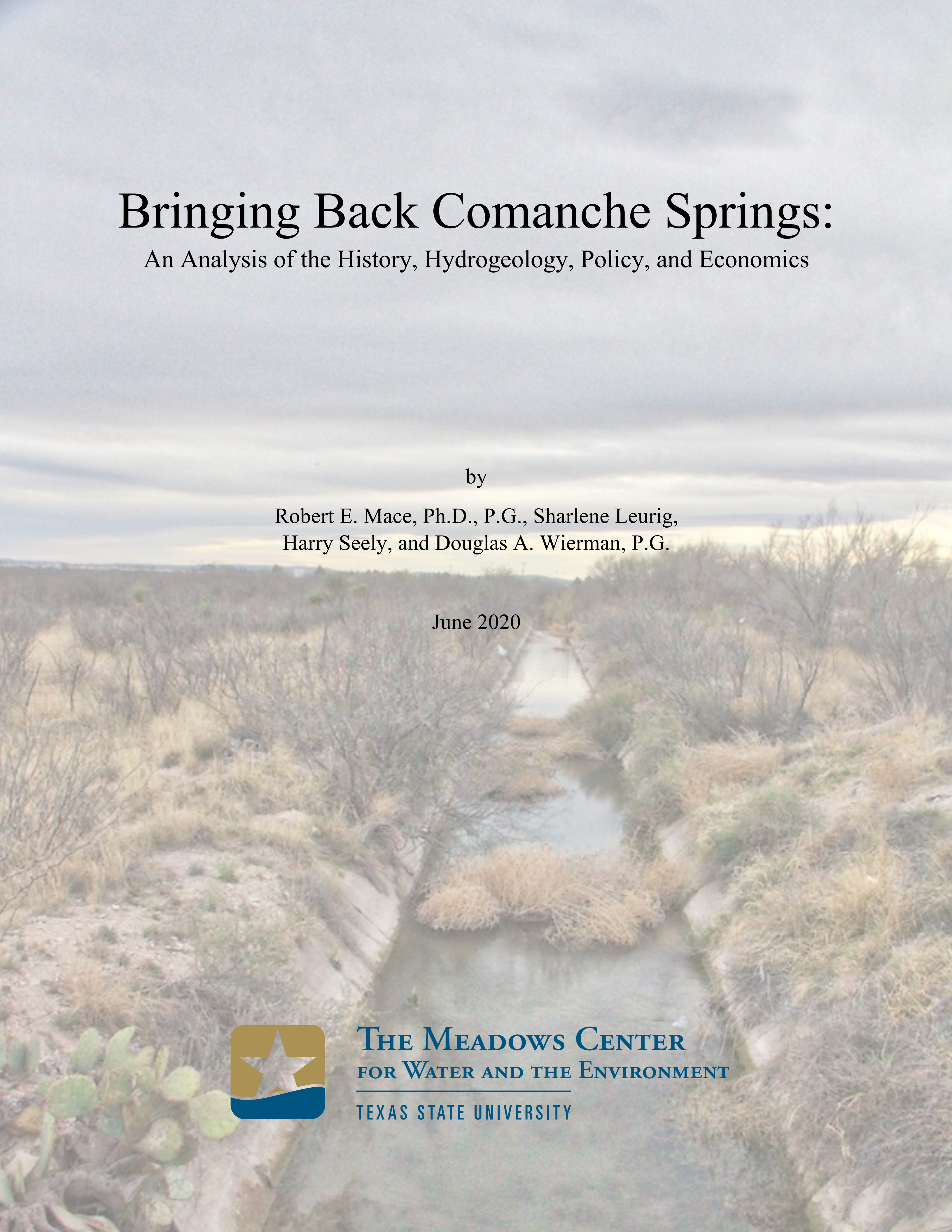

Bringing Back Comanche Springs:

An Analysis of the History, Hydrogeology, Policy, and Economics

by

Robert E. Mace, Ph.D., P.G., Sharlene Leurig,
Harry Seely, and Douglas A. Wierman, P.G.

June 2020

The Meadows Center
for Water and the Environment
Texas State University

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THE MEADOWS CENTER
FOR WATER AND THE ENVIRONMENT
TEXAS STATE UNIVERSITY

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An Analysis of the History, Hydrogeology, Policy, and Economics

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Robert E. Mace[a], Ph.D., P.G., Sharlene Leurig[b], Harry Seely[c], and Douglas A. Wierman[d], P.G.

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June 2020

A report for
the National Fish and Wildlife Foundation,
the Fort Stockton Convention and Visitors Bureau, and
the Cynthia and George Mitchell Foundation

The use of brand names in this report does not indicate endorsement by the authors, the authors' employers, or the funders.

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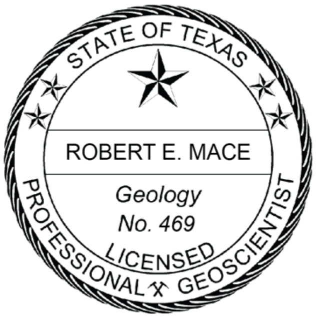

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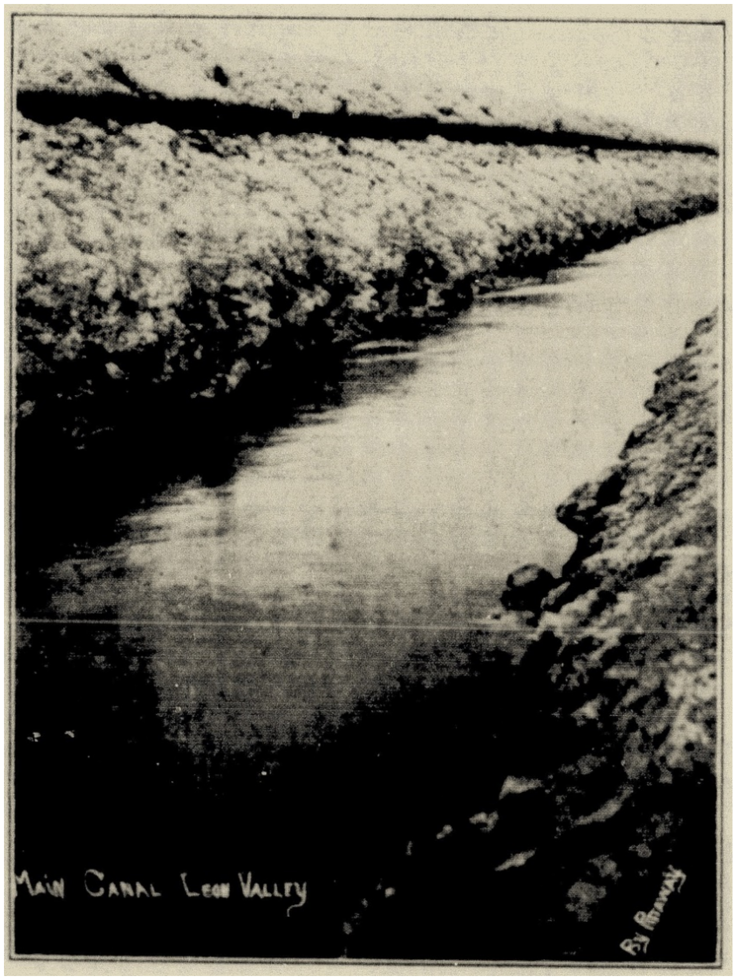
Mr. Wierman contributed to the content on describing the geologic setting; aquifers; and pumping, desired future conditions, and modeled available groundwater. Dr. Mace contributed to these sections and all other hydrogeologic work and review.



The Leon Springs are the real thing.
Messrs Beeman and Mills can show,
In Summer, Fall, Winter, and Spring,
What the Leon Valley will grow.

The alfalfa hay, which begins coming in May,
Is of the purest emerald green.
When prices are right, it finds its way
To distant and less favored scenes.

The cattle are fine, and so are the swine,
And the horses are of noble strain.
The men, well, they are two of a kind,
None better from Texas to Maine.

-anonymous

Published in the Fort Stockton Pioneer on April 9, 1915.

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Executive Summary

Comanche Springs, once the sixth largest spring in Texas, has a long and storied history, from mammoths sipping its brackish flow to hosting conquistadors and frontier forts to irrigating thousands of acres to being the focus of a key court decision. Unfortunately, due to pumping seven miles to the west, the springs started to fail in 1947 and stopped flowing in 1961 for 25 years. Along with the loss of Fort Stockton's natural swimming hole and the livelihoods of more than 100 families downstream was an ecosystem that supported several species now recognized as endangered, including the Comanche Springs pupfish. In 1986, the springs sprang back for a couple winters, disappeared, and then returned off and on in ensuing decades. Consistent winter flow over the past decade had posed the question: What would it take to bring flows back over the entire year? Therefore, the purpose of this study was to conduct an historical, hydrogeologic, policy, and economic review to inform residents, regulators, and policymakers on what it would take for Fort Stockton to call itself Spring City once again.

By evaluating historic hydrogeologic reports and newspaper accounts of the development of spring-fed irrigation at Leon and Comanche springs and pump-fed irrigation in the Leon-Belding Irrigation Area, we compiled the most comprehensive, quantified timeline of known hydrologic events for the flow system. Most importantly, we rediscovered the flow-enhancing wells drilled at Leon Springs between 1915 and 1916 and reconstructed, through newspaper reports and analysis, how much these wells enhanced flow at the springs (and decreased flow at Comanche Springs). This rediscovery has implications for the system's water budget, estimates of pumping and recharge in the numerical groundwater flow models, and the long-term sustainable management of the aquifer. A systematic analysis of historical estimates of pumping and springflows reveals that the currently used groundwater model tends to overestimate pumping by about 50 percent and that a simple water budget approach can be used to explain flows in the system and, in turn, estimate pumping when there is flow at Comanche Springs.

The Middle Pecos Groundwater Conservation District describes its mission as helping to "…maintain a sustainable, adequate, reliable, cost effective and high-quality source of groundwater to promote the vitality, economy and environment of the District." The district's rules include aquifer-based production limits based on achieving the desired future conditions of aquifers in the district, including within management zones, one of which encompasses the flow system for Comanche Springs. The district's current management approach, while seeking to achieve sustainability, is not amenable to creating a water market to maintain springflows because, overall, while pumping is limited, permits are not. There are several options the district could employ to limit permits in addition to pumping, including a correlative rights approach for production permits (which do not include historic and existing uses) in Management Zone 1.

Based on results of a topographic survey, state code on turnover in pools, and nearby spring analogues of flow for pupfish and other species, we estimated that daily flow through a restored natural pool at Comanche Springs needs to be at least 10 cubic feet per second for health and human safety and species requirements. Because of seasonal variations due to irrigation pumping, we determined that average annual springflow needs to be 20 cubic feet per second to achieve this minimum. Using a variety of methods, we identified that pumping needs to be between 26,000 to 35,000 acre-feet per year (with the lower number more likely) to achieve at least 10 cubic feet per second of daily flow at Comanche Springs.

We evaluated six different alternatives to reduce groundwater pumping in the Edwards-Trinity Aquifer. Leasing full season permits could reduce pumping by 8,400 acre-feet per year at a cost of $75 to $150 per acre-foot. Leasing partial season permits could reduce pumping by 1,800 acre-feet per year at a cost of $75 to $150 per acre-foot. Improving irrigation efficiency could reduce pumping by 2,000 acre-feet per year at a cost of $50 per acre-foot. Switching crops could reduce pumping by 2,250 acre-feet per year at a cost of $1,067 per acre-foot. Switching sources could reduce pumping by 9,235 acre-feet per year at a capital cost of $735 per acre-foot and an annual operating cost of $144 per acre-foot. Purchasing permits could reduce pumping by more than 9,200 acre-feet per year (we did not identify a cost for this alternative due to on-going price negotiations).

We also identified funding sources to implement the alternatives, including WaterSMART, U.S. Fish and Wildlife Service Section VI, Natural Resources Conservation Service, Texas Water Development Board Agricultural Conservation Program, state revolving funds, State Water Implementation Fund for Texas, pool entry fees, tax revenues from increased non-local spending, water sales, municipal bonds, outcomes-based bonds, and private equity. The restoration of Comanche Springs could—and likely would—be enabled through a blending of these various financial resources. What makes the restoration of Comanche Springs viable is the multiple economic and ecological benefits that restored surface flows would achieve. Project sponsors would be right to think of restoring Comanche Springs primarily as an economic development project. Total pledgeable new revenues from non-local visitation to a restored Comanche Springs could amount to $1.9 million a year.

We believe the next steps involve a multi-pronged approach, some of which is already in process, such as establishing a pilot market, incentivizing on-farm efficiency improvements, and improving the groundwater model. Given the importance of pumping estimates, not only to estimating the amount of pumping needed to maintain year-round springflow but also to managing groundwater resources in Management Zone 1, we strongly recommend a thorough analysis of pumping in the Leon-Belding Irrigation Area, especially since the current model is calibrated with overestimated pumping and is currently being updated. The groundwater district should also measure spring-flow in real-time to not only have flow for Comanche Springs but also serve to check pumping estimates. Finally, the groundwater district should explore what it may be willing to do to limit permitted volume, and there should be discussions on which pumping reduction strategies users would be willing to do.

While there have been a number of hydrogeologic studies conducted over the past 70 years, this is the first to fully assemble the history of the flow system and evaluate the policy and economics of bringing year-round flow back to Comanche Springs. While challenges remain large, we have developed the first roadmap to restoring the springs. Opportunity waits.

1.0 Introduction

Once the sixth largest spring in Texas (Sharp 2001), Comanche Springs produced its last trickles on March 19, 1961, before going dry for more than 25 years. These historic springs, having previously flowed for thousands of years, were a watering hole for mammoths, camels, and sloths during the last ice age and sustained a vibrant desert ecosystem through the 1950s. Humans have used the springs for at least 20,000 years, first serving as water stops for thirsty travelers, then hosting the namesake garrison for Fort Stockton, and then providing irrigation water for more than 100 downspring families, turning a brown valley green.

The springs have not flowed reliably since the 1950s when pump-fed irrigated agriculture expanded in the Leon-Belding area about eight miles west. Significant groundwater production in the Edwards-Trinity Aquifer in this area caused spring flows to decline precipitously in the 1950s and led to a seminal court case, Pecos County Water Control and Improvement District No. 1 v. Williams and others, which determined that, under the Rule of Capture, no liability could be assessed against groundwater irrigators, even if they caused springs to stop flowing and affected the surface-water rights of downspring irrigators. Soon after the court's decision, farms along Comanche Creek were entirely extirpated, as were the populations of desert fish that once thrived in the springs.

In October 1986, Comanche Springs gurgled back to life, igniting memories of days gone by, inspiring a study on the hydrogeology of the area, and sparking an attempt to form a groundwater conservation district, later created and confirmed in 1999 and 2002, respectively. Since at least 2011, springflows have returned every winter season, drawing visitors and bringing a twinkle to the dwindling number of local eyes who remember when the springs flowed freely into its natural basin.

The consistent return of seasonal flow to Comanche Springs over the past decade begs the question: What would it take to bring flows back over the entire year? This is a question that requires a study of the history of the springs and pumping in the area, a review of what is known about the science of the aquifer, an assessment of the economics, and an appraisal of local groundwater policy. Although there have been a number of scientific studies of the aquifers in the area over the past 100 years, none have put the science in the context of the history of what happened, the policy that exists, or the economics of returning year-round flow to the springs. The purpose of this study was to conduct an historical, hydrogeologic, policy, and economic review to inform residents, regulators, and policymakers on what it would take for Fort Stockton to call itself Spring City once again. Although this project is focused on a small, but storied, part of West Texas, the general intersection of history, science, policy, and economics is relevant to the rest of Texas—or anywhere, really—where springs have been impacted by pumping and where discussions are focused on the sustainable development of groundwater.

2.0 Study Area

The study area is in Pecos County where the High Plains lap up against the Basin and Range Province in West Texas (Wermund 1996). The High Plains form a nearly flat plateau which, in the study area, is part of the Edwards Plateau, while the Basin and Range Province is represented by mountain ranges alternating with basins (Wermund 1996). More locally, the study area extends from the east side of Fort Stockton where Comanche Springs issue from, west seven miles along a presumed flow path toward the now-defunct Leon Springs, south of Interstate 10 through the Leon-Belding Irrigation Area and then south to the Glass Mountains (Figure 2.1). Average annual temperature is about 60° Fahrenheit, average annual rainfall is about 15 inches, and average annual gross lake evaporation is about 75 inches (TWDB 2012). Land-surface elevation slopes from about 5,000 feet above sea level in the Glass Mountains to 2,900 to 3,000 feet along Interstate-10.

Fort Stockton is the county seat for Pecos County and is by far the largest community in the county with an estimated 8,318 residents as of July 1, 2018 (U.S. Census Bureau 2020). The community of Belding was platted in 1913 along the railroad but, due to the cost of pumping water, was never realized; its hotel was later moved to Leon Lake (Justice 2010a).

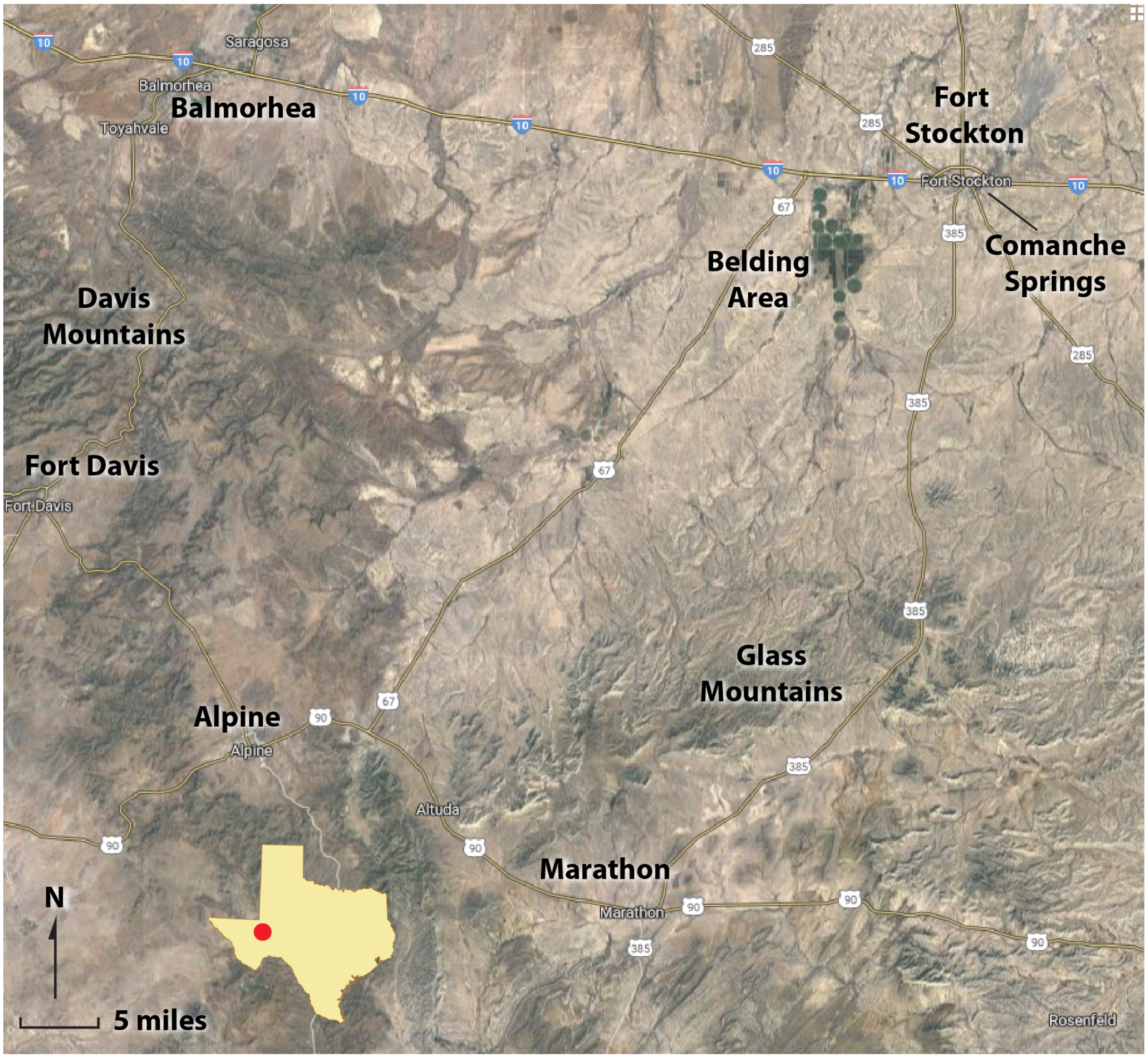
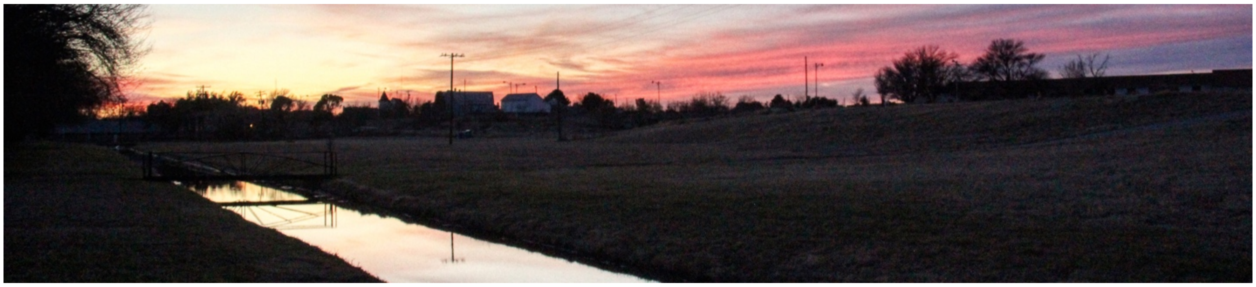


Figure 2.1: Study area (base map from Google 2020).



3.0 A Series of Springs

There are several historical springs and at least one still-flowing spring in the area. Comanche Springs on the east side of Fort Stockton was the largest (Figure 3.1) with a flow of 40 to 45 cubic feet per second between 1919 and 1949 (Atkins 1927; Armstrong and McMillion 1961) and two measurements—one in summer 1899 and one on July 26, 1904—of 66 and 64 cubic feet per second, respectively (Meinzer 1927; Taylor 1902 reports a value of 70 cubic feet per second for 1899). Total dissolved solids in Comanche Springs was about 1,330 parts per million between 1932 and 1958 (USGS 2020a) with a reported constant water temperature of 72° F (temperatures measured for flow reappearances in 1987 and 1991 were 64° F and 70° F, respectively [USGS 2020a]).

As the name indicates, there are several major, minor, and unnamed springs that make up the Comanche Springs, including Main or Big Chief Spring and Government Spring, both at the modern-day pool (Figure 3.2). These two springs are at the lowest elevation of the spring complex. Heading up-stream, there's Koehler's Spring, Blue Hole, Church Spring, Jail Spring, and Head Water Spring along with various unnamed seeps and springs along the way (Collett 2011). Baker and Bowman (1917) described the springs as either fissure springs rising along fault lines or springs in solution channels. Before the springs failed, Comanche Creek reportedly flowed four miles downstream before sinking into the ground (Adkins 1927, Williams 1982 p132).

There were also several springs downstream from Comanche Springs (Figure 3.1), the most prominent being San Pedro Spring, which flowed 3.6 to 4.9 cubic feet per second before 1951 (Armstrong and McMillion 1961; Brune 1975). To the southeast of San Pedro Spring, on the opposite bank of Comanche Creek, was Cold Spring (Figure 3.1) which flowed 2.55 cubic feet per second on October 16, 1942 (Parker and others 1944, USGS 2020a). Cold Spring was known for its "ice cold" water (Fort Stockton Pioneer 1908b) and provided enough flow for fishing (Fort Stockton Pioneer 1915e). Further downstream near the intersection of 1053 and Buena Vista Road there was San Simon Spring (80 gallons per minute [0.21 cubic feet per second] on May 11, 1943, with a temperature of 64° F [Dante 1947]), Adobe Springs (170 gallons per minute [0.45 cubic feet per second] on October 28, 1932 [Dante 1947]), Johnson Spring (140 gallons per minute [0.37 cubic feet per second] on May 12, 1943, with a temperature of 65° F [Dante 1947]), and Travertine Spring (Dante 1947). Veni (1991) speculated that the primary discharge point in the Comanche Creek area was 33 to 43 feet

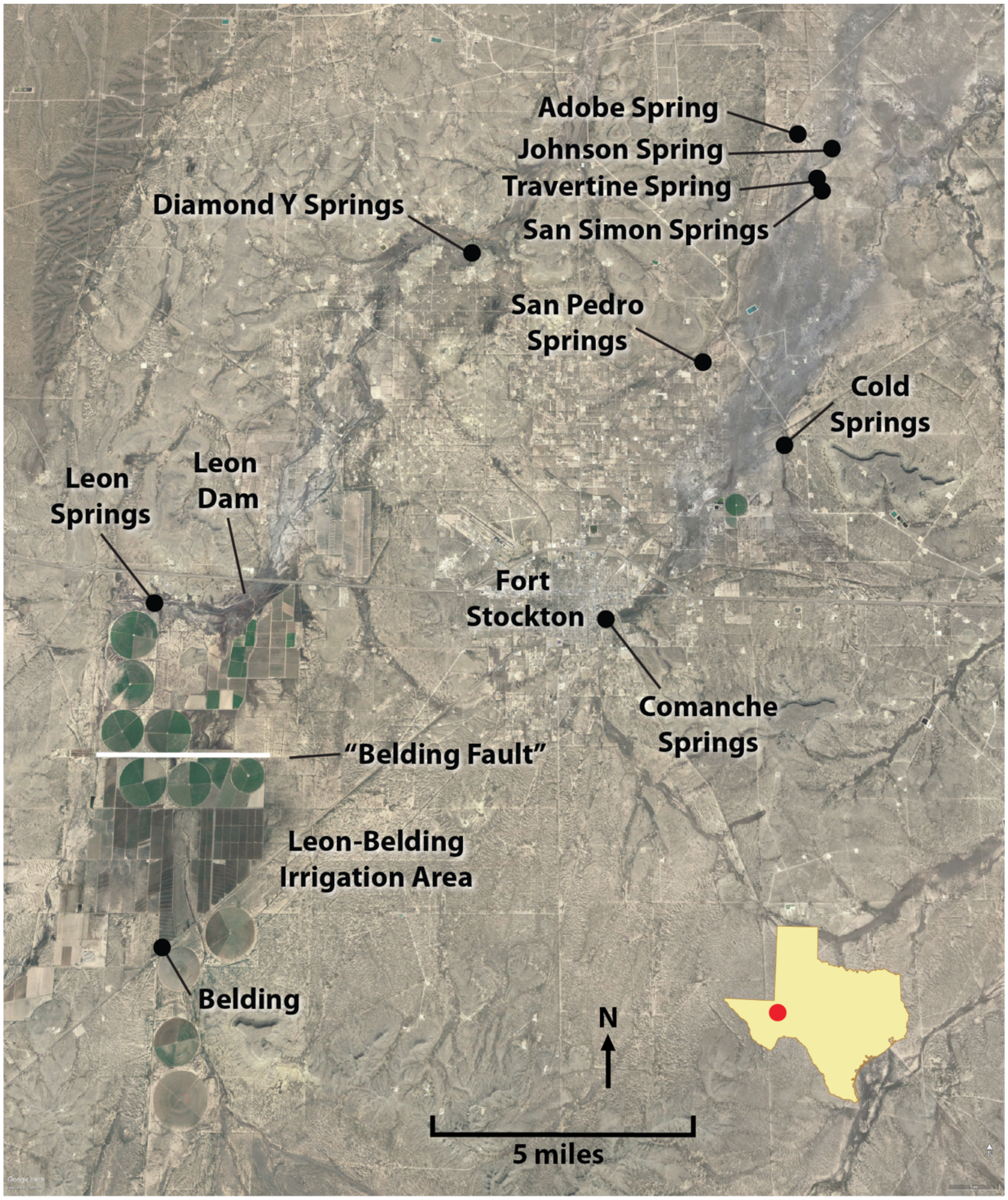


Figure 3.1: Study area showing springs, Leon Dam, and the Belding Fault (base map from Google 2020).

Figure 3.2: Comanche Springs (based on maps from Brune 1981, Small and Ozuna 1993, and Collett 2011; base map from Google 2020). Small and Ozuna (1993) show a Main Spring beneath the pool in addition to Chief and Government whereas Collett (2011) shows Big Chief and Main being the same spring. Solid circles represent spring locations that still show evidence today of their existence. Open circles are approximate spring locations with no evidence today of their existence.

lower that Big Chief and Government springs and moved uphill as the creek valley was capped with alluvial fill during the Pleistocene.

In the Leon-Belding Irrigation Area, there was Leon Springs (Figure 3.1), referred to historically as Leon Holes since the springs issued from three natural holes that averaged 30-feet in diameter and 20-feet deep (Williams 1923, Williams 1982). Flows at the springs were about 10,000,000 gallons per day (about 15.5 cubic feet per second; Fort Stockton Pioneer 1911a) with total dissolved solids of 1,416 parts per million (Fort Stockton Pioneer 1911b). Flow at Leon Springs (which included by this time flows from five nearby flowing wells) ranged from 23 cubic feet per second for water year 1920 to 14 cubic feet per second for water year 1946 before drying up for good in 1958 (Brune 1975). Armstrong and McMillion (1961) noted that Leon Springs and a few nearby wells produced about 9,000 acre-feet per year (12.4 cubic feet per second) prior to 1946.

About 10 miles to the northeast, farther down Leon Creek, is Diamond Y Spring, which flowed at 0.43 cubic feet per second on May 10, 1943 (USGS 2020a); had no reported flow in 1971 (Brune 1975); was flowing in 1987 (Veni 1991); was flowing in 1990 (Boghici 1997); flowed 0.43 cubic feet per second on January 1, 1992; flowed between 0.0 and 0.25 cubic feet per second between October 27, 2010, and December 12, 2014 (USGS 2020a); and continues to flow today. Veni (1991) reported much higher flows at between 1.4 and 2.1 cubic feet per second at Diamond Y Spring proper and 3.2 to 5 cubic feet per second for the entire spring complex. Total dissolved solids measured on August 8, 2010, was 5,000 parts per million with a temperature of 69° F (USGS 2020a).

Land-surface elevations, from highest to lowest, are ~3,000 feet above sea level at Leon Springs; ~2,940 feet at Head Spring and ~2,930 feet at Big Chief Spring, both part of Comanche Springs; ~2,830 at Cold Springs; ~2,810 feet at San Pedro Spring; 2,790 feet at Diamond Y Spring; and ~2,670 feet at San Simon Spring (based on data from USGS 2020b).[1]

Out of the study area in the Balmorhea area (Figure 2.1), about 50 miles to the west of Fort Stockton, are San Solomon, Phantom Lake, Saragosa, Giffin, and East and West Sandia springs.

[1] Elevations for several of the springs listed are approximate because the exact location of the springs are approximate.

4.0 Hydrogeology

The study area includes geology and aquifers of Permian (Capitan Reef and Rustler aquifers), Triassic (Dockum Aquifer) and Cretaceous (Edwards-Trinity [Plateau] Aquifer) ages as well as Cenozoic-aged sediments (Pecos Valley Aquifer) (Bumgarner and others 2012; Figure 4.1). Dissolution of Permian salts when the Cretaceous rocks were deposited created the Belding-Coyanosa Trough that cuts north-south through the study area (Figure 4.2). The faulting that resulted from this dissolution is a key geologic component for the existence of the Leon-Belding Irrigation Area, Leon Springs, Comanche Springs, and other springs in the area. An approximately east-west cross-section through the study area (Figure 4.3) shows that the Edwards rocks in the Leon-Belding Irrigation Area are down-dropped about 500 feet, creating a local basin of karstified limestone in the area (Figure 4.4).

4.1 Edwards-Trinity (Plateau) Aquifer

The Edwards-Trinity (Plateau) Aquifer (referred to hereafter as the Edwards-Trinity Aquifer) is a major aquifer of Texas (George and others 2011), underlies the entire study area, and is the primary source of water in the area as well as the source of much of the water for irrigation in the Leon-Belding Irrigation Area and spring flows to Comanche Springs (Figure 4.5). The Edwards part of the aquifer consists of limestone, marl, and clay (Clark and others 2013) and yields small to large amounts of water (Rees and Buckner 1980) while the Trinity part of the aquifer consists of sand, limestone, and shale (Clark and others 2014) and yields small to large amounts of water (Rees and Buckner 1980; small is less than 50 gallons per minute, moderate is 50 to 500 gallons per minute, and large is more than 500 gallons per minute). Although groundwater is available in both the Edwards and Trinity parts of the aquifer, the Edwards part is far more productive. Limestones of the Edwards—with caverns reported to be as large as

Era	Period	Series or group		Stratigraphic unit			Major and minor aquifers	Model layer
Cenozoic	Quaternary and Tertiary			Alluvium			Pecos valley	Alluvial layer
Cenozoic	Tertiary			Volcanic Rocks, undivided			Igneous	
Mesozoic	Cretaceous	Gulfian Series	Terlingua Group	Boquillas Formation				
Mesozoic	Cretaceous	Comanchean Series	Washita Group	Western Pecos County		Eastern Pecos County	Edwards-Trinity	Edwards layer
Mesozoic	Cretaceous	Comanchean Series	Washita Group	Sixshooter Group	Buda Limestone	Buda Limestone	Edwards-Trinity	Edwards layer
Mesozoic	Cretaceous	Comanchean Series	Washita Group	Sixshooter Group	Boracho Formation	Edwards Group: Fort Lancaster Formation	Edwards-Trinity	Edwards layer
Mesozoic	Cretaceous	Comanchean Series	Washita Group	Sixshooter Group	University Mesa Marl	Edwards Group: Burt Ranch Member	Edwards-Trinity	Edwards layer
Mesozoic	Cretaceous	Comanchean Series	Fredericksburg Group	Sixshooter Group	Finlay Formation	Edwards Group: Fort Terrett Formation	Edwards-Trinity	Edwards layer
Mesozoic	Cretaceous	Comanchean Series	Trinity Group	Trinity Sands	Maxon Sand		Edwards-Trinity	Trinity layer
Mesozoic	Cretaceous	Comanchean Series	Trinity Group	Trinity Sands	Glen Rose Formation		Edwards-Trinity	Trinity layer
Mesozoic	Cretaceous	Comanchean Series	Trinity Group	Trinity Sands	Basal Cretaceous Sand		Edwards-Trinity	Trinity layer
Mesozoic	Triassic	Dockum Group		Middle			Dockum	Dockum layer
Mesozoic	Triassic	Dockum Group		Lower			Dockum	Dockum layer
Paleozoic	Permian	Ochoan Series		Southern Pecos County	Northern Pecos County			
Paleozoic	Permian	Ochoan Series		Tessey Limestone	Rustler Formation		Rustler	Rustler layer
Paleozoic	Permian	Ochoan Series		Tessey Limestone	Salado Formation			
Paleozoic	Permian	Ochoan Series		Tessey Limestone	Castile Formation			
Paleozoic	Permian	Guadalupian Series	Whitehorse Group	Gilliam Limestone	Capitan Limestone	Guadalupian Formations; undivided	Capitan Reef	
Paleozoic	Permian	Guadalupian Series		Lower Guadalupian Formations; undivided				
Paleozoic	Permian			Lower Permian Formations; undivided				
Paleozoic	Pennsylvanian			Pennsylvanian Formations; undivided				

Figure 4.1: Hydrogeologic section of the study area (modified from Clark and others 2013; modifications include the highlighting of the aquifers and dissolving the line for the Edwards-Trinity Aquifer between the Edwards and Trinity layers, an error in the original).

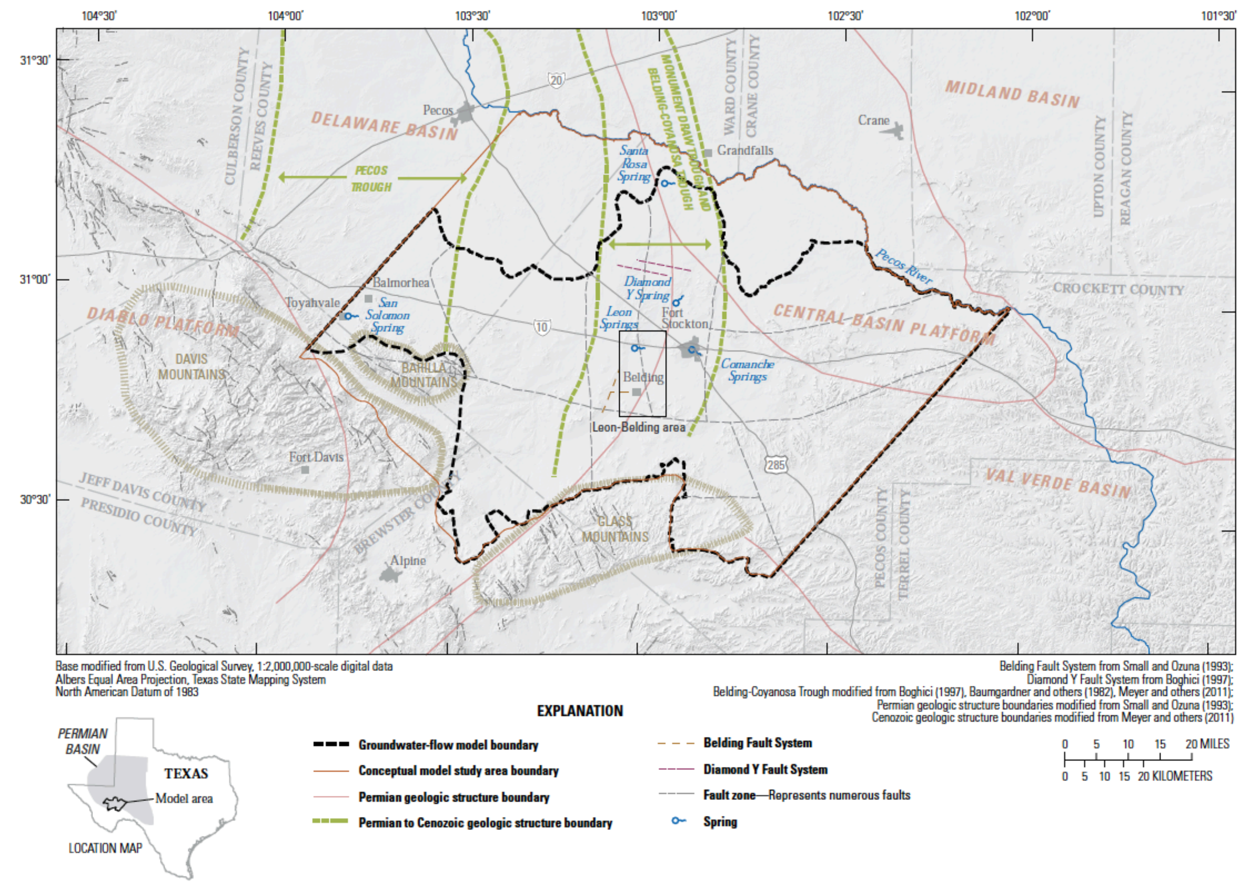


Figure 4.2: Major geologic structural features in the greater Pecos County area (from Clark and others 2013).

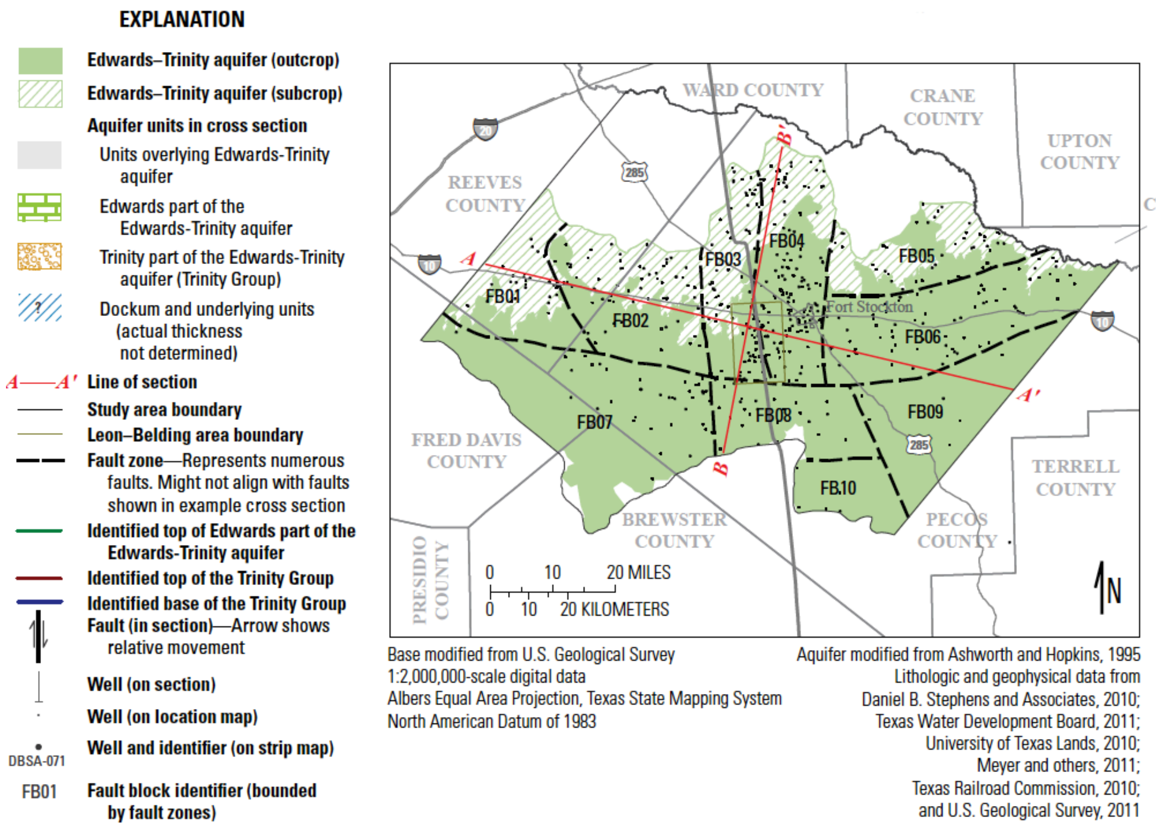


Figure 4-3: Location for the cross-section shown in Figure 4.4 (from Bumgarner and others 2012).

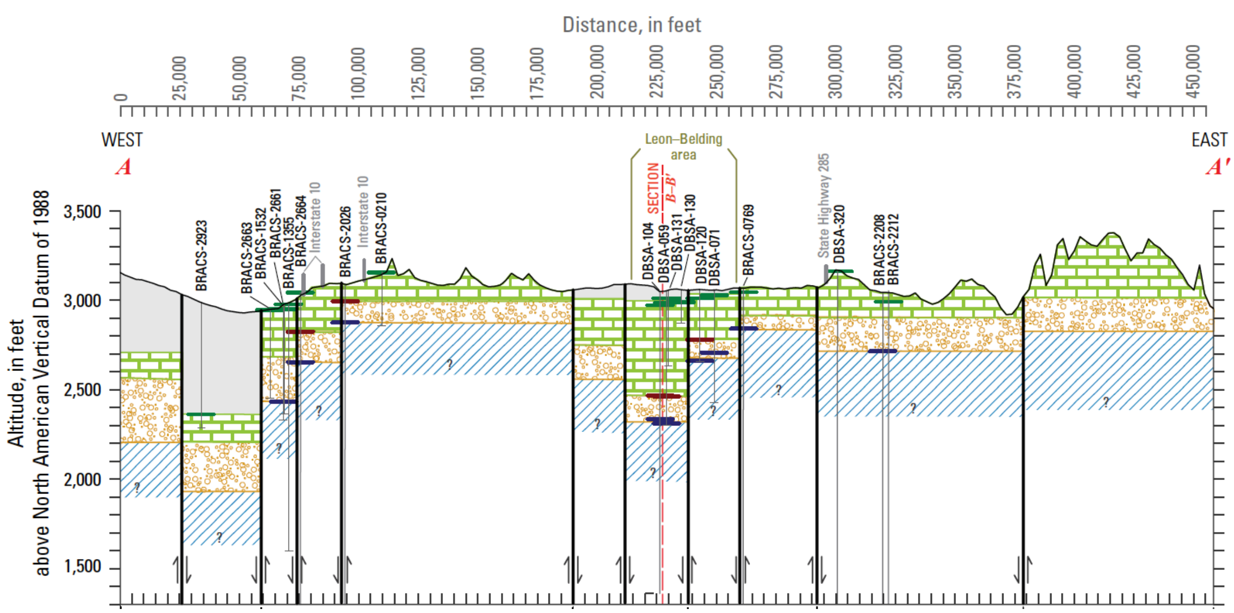


Figure 4.4: An approximately east-west cross-section through the study area (location of the cross-section shown in Figure 4.3; from Bumgarner and others [2012]).

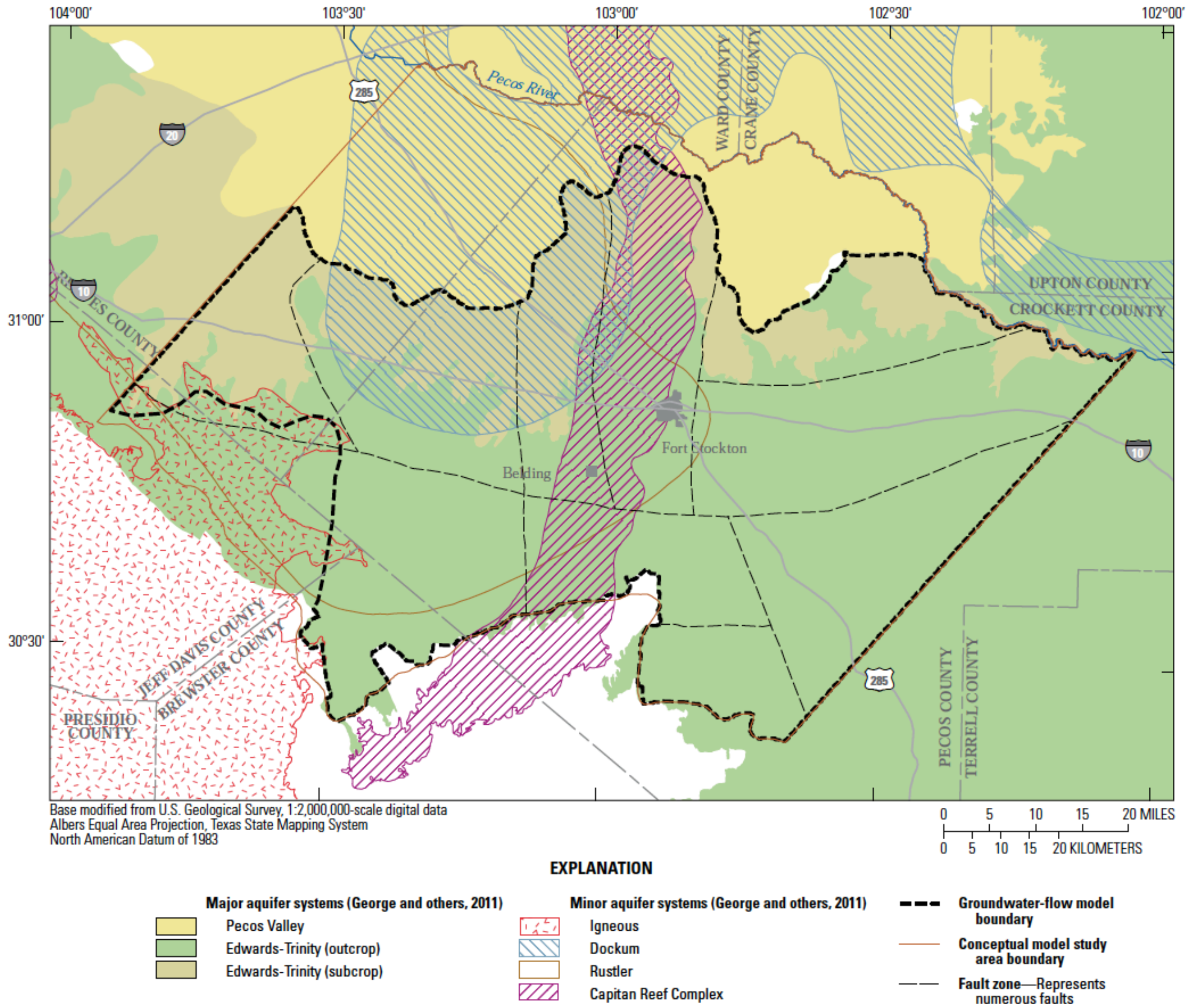


Figure 4.5: Major and minor aquifers in the study area (from Clark and others 2013).

eight feet—can produce as much as 3,000 gallons per minute (Audsley 1956, Armstrong and McMillion 1961).

Armstrong and McMillion (1961) note that the productive parts of the Edwards-Trinity Aquifer in the Leon-Belding Irrigation Area are mostly limited to a five-mile wide area between the locally-known Belding Fault (which lies approximately along Srangus Road; Figure 3.1) to two miles south of this fault with a one-mile-wide productive area south of that. The current distribution of agriculture suggests that there is a productive zone north of the Belding Fault probably along a flowpath to Leon Springs.

Groundwater is under water-table conditions in the Edwards-Trinity Aquifer in the study area although artesian conditions have been observed in the Leon-Belding Irrigation Area north of the Belding Fault where the Edwards rocks are overlain with clays (Armstrong and McMillion 1961). Regional groundwater flow directions are generally to the north and northeast towards the Pecos River Bumgarner and others (2012). Bumgarner and others (2012) interpreted a groundwater divide between the northern Leon-Belding Irrigation Area and Comanche Springs near Twomile Hill during winter water levels, a divide that then cuts across the Leon-Belding Irrigation Area. Given the faulting and karstification in the Leon-Belding Irrigation Area and through a flowpath to Comanche Springs, anisotropy complicates using the potentiometric surface to identify local flowpaths.

Hydraulic gradients in the Leon-Belding Irrigation Area show a lower gradient south of the Belding Fault than north of it (Bumgarner and others 2012 p 44), suggesting greater aquifer productivity to the south and lower aquifer productivity to the north, something that is observed in the field. The flowpath to Comanche Springs may begin on the eastern end of the Belding Fault in the irrigation area.

4.2 Dockum Aquifer

The Dockum Aquifer is a minor aquifer of Texas (George and others 2011) and extends into the northwestern part of the study area (Figure 4.5), although the rocks that make up the Dockum Aquifer extend beneath the study area with poorer water quality. The Dockum Aquifer consists of shale, sand, sandstone, and conglomerate (Clark and others 2014) and can yield small to moderate amounts of water (Rees and Buckner 1980). There is little information on the Dockum Aquifer in the study area. Because the Dockum Aquifer consists mostly of shale in the study area and yields much less water than the overlying Edwards-Trinity Aquifer, it is considered a confining layer (Clark and others 2014), a hydrologic feature that generally impedes groundwater flow.

4.3 Rustler Aquifer

The Rustler Aquifer is a minor aquifer of Texas (George and others 2011) and exists under most of the study area (Figure 4.5). The Rustler Aquifer consists of dolomite, anhydrite, and some limestone with a basal unit of sand, conglomerate, and some shale (Clark and others 2014) and yields small to moderate amounts of slightly to moderately saline water (Rees and Buckner 1980). The dolomite and limestone have vugular porosity and are reported to be cavernous in places (Small and Ozuna 1987). Wells completed in the Rustler Aquifer have been developed to supplement the Edwards-Trinity wells in the Belding area (Rees and Buckner 1980). Groundwater in the Rustler appears to move from south to north in the study area, although data is sparse (George and others 2011). The aquifer is under artesian conditions in the Leon-Belding Irrigation Area based on data collected by the Middle Pecos Groundwater Conservation District.

4.4 Capitan Reef Complex Aquifer

The Capitan Reef Complex Aquifer (hereafter referred to as the Capitan Reef Aquifer) is a minor aquifer of Texas (George and others 2011) that extends through the heart of the study area (Figure 4.5). This aquifer directly underlies the Rustler Aquifer west of Fort Stockton;

consists of massive, poorly bedded limestone, dolomite, and reef talus; and has a maximum thickness of about 1,650 feet (Small and Ozuna 1993). The reef occurs in a 6- to 10-mile-wide, south-southeast trending belt, extending from New Mexico through western Winkler, central Ward, and western Pecos counties. Depth to the top of the aquifer in the study area ranges from 2,400 to 3,600 feet (Ashworth 1990).

There is little data available in the Leon-Belding Irrigation Area on hydrologic conditions in the Capitan Reef Aquifer. Because of its depth and moderately saline water, the Capitan Reef Aquifer has not been an important aquifer in Pecos County; however, with limited water supplies in West Texas, there is growing interest in tapping it resources. The aquifer is under artesian conditions in the study area based on data collected by the Middle Pecos Groundwater Conservation District. The district has one monitoring well completed in the Capitan Reef Aquifer with a relatively short period of record.

4.5 Cross-Formational Flow

Cross-formational flow is when water moves from one hydrogeologic unit to another. In the present case, we are focused on how water may or may not flow from one aquifer to another. In general, for cross-formational flow to occur between adjacent or stacked aquifers, two conditions must exist. First, there must be a hydraulic head difference between the two adjacent formations (in other words, one aquifer has a higher water pressure than an adjacent aquifer creating the potential for water to move from the higher-pressured aquifer to the lower-pressured aquifer). Second, there must be a pathway to allow water to move from one aquifer to another. Potential pathways may include through a confining layer, fractures, faults, or karst features.

Armstrong and McMillion (1961) speculated that water may flow from the Rustler Aquifer into the Edward-Trinity Aquifer in this part of Pecos County. Bumgarner and others (2012) analyzed water-level data from two wells in the Edwards-Trinity Aquifer and two wells in the Rustler Aquifer to determine vertical gradients between the two aquifers in the Leon-Belding Irrigation Area. They determined that vertical gradients were upward from the Rustler Aquifer towards the Edwards-Trinity Aquifer, with hydraulic head differences ranging from 83 to 121 feet (hydraulic head is a measure of water "pressure" in an aquifer). This pressure difference indicates the potential for water to move from the Rustler Aquifer to the Edward-Trinity Aquifer.

We acquired water-level data from the Middle Pecos Groundwater Conservation District in three wells in the Leon-Belding Irrigation Area, one in each for the Capitan Reef Aquifer, the Rustler Aquifer, and the Edwards-Trinity Aquifer, and plotted them together (Figure 4.6). These water-level data confirm Bumgarner and others' (2012) conclusions that there are upward vertical gradients from the Capitan Reef Complex Aquifer to the Rustler Aquifer and, in turn, from the Rustler Aquifer to the Edwards-Trinity Aquifer. The average hydraulic head difference between the Edward-Trinity and Rustler aquifers is 125 feet with a hydraulic head difference between the Capitan Reef Complex and Rustler aquifers of 47 feet.

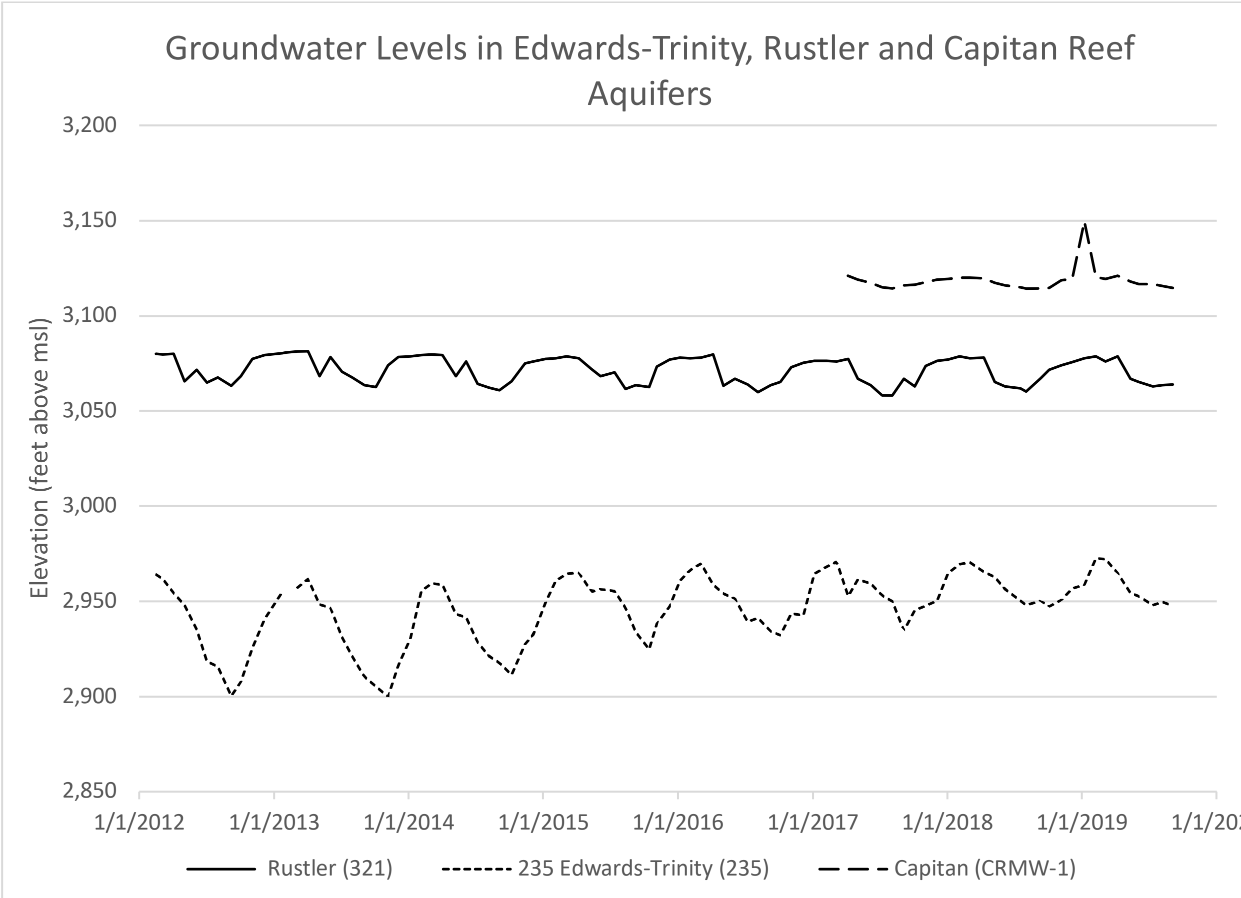


Figure 4.6: Groundwater levels in Edwards-Trinity, Rustler, and Capitan Reef aquifers (data from the Middle Pecos Groundwater Conservation District; msl = mean sea level).

Potential pathways in the Leon Belding Irrigation Area include general upward groundwater flow across the geologic layers but also the faulting associated with Belding-Coyanosa Trough that cuts though the study area. Hiss 1976 (as referenced in Small and Ozuna 1993) suggested that a connection between the Capitan Reef Aquifer and the Edwards-Trinity Aquifer probably occurs where joints, fractures, and faults are well developed.

Similarly, Ashworth (1990), Boghici (1997), and Bumgarner and others (2012) suggested that upwelling is likely the result of groundwater flow from underlying aquifers along fault zones. Small and Ozuna (1993) hypothesized that flow may occur in areas where a Triassic shale unit that separates the Trinity Group of the Edwards-Trinity Aquifer from underlying units is absent.

While hydraulic head differences and faulting suggest cross-formational flow is possible, it does not prove that cross-formational flow is occurring. Comparing water chemistry between the aquifers is a way to confirm aquifer-to-aquifer connections. The first clue to this is that water in the Edwards-Trinity Aquifer in the Leon-Belding Irrigation Area and from Comanche

Springs is brackish, generally around 1,500 milligrams per liter (Dennis and Lang 1941, Boghici 1997). In general, water quality in the broader Edwards-Trinity Aquifer is fresh, typically less than 1,000 milligrams per liter (Anaya 2004). Given the proximity of the Leon Belding Irrigation Area to the recharge zone for the Edwards-Trinity Aquifer (20 miles to the south), it is unlikely that water in the Edwards-Trinity Aquifer would be as saline as it is without cross-formational flow from more saline aquifers beneath it. Total dissolved solids in the Rustler Aquifer in the Leon-Belding Irrigation Area is also about 1,500 milligrams per liter (Boghici 1997) while two wells in the Capitan Reef Complex Aquifer in the Leon Belding Irrigation Area range from 1,100 to 1,900 milligrams per liter. Higher salinities suggest that Edwards-Trinity water is mixing with more saline groundwater or dissolution of evaporites (Bumgarner and others 2012).

Oxygen and hydrogen isotopes in groundwater can be used to assess when groundwater was recharged (see, for example, Uliana and others 2007). These isotopes suggest that groundwater from the Edwards-Trinity Aquifer in the study area is a mixture of recent, local recharge and older water that recharged under a different climate (Bumgarner and others 2012). Oxygen and hydrogen isotopes measured in the Rustler Aquifer in the Leon-Belding Irrigation Area, in the Capitan Reef Aquifer, and in Comanche Springs suggest that most of the water is older recharge (consistent with the findings of Uliana and others 2007); however, the detection of atrazine and elevated nutrients in the Leon-Belding Irrigation Area and Comanche Springs suggests a local source of recharge as well (Bumgarner and others 2012). Bumgarner and others (2012) noted that although there is a local component of recharge, it only occurs at the mountain front and in areas receiving irrigation return flows. Relatively steady springflow from year-to-year before groundwater pumping increased in the late 1940s also suggests a broader and older source of water to the springs. Harden and others (2011) pointed to soil studies to conclude that there was no irrigation return flows in the Leon-Belding Irrigation Area; however, the subsequent detection of pesticides and elevated nutrients in the area suggest otherwise.

5.0 Use and Development

The use and development of water at the springs has four broad phases: (1) pre-irrigation, (2) spring irrigation, (3) groundwater irrigation, and (4) groundwater export. We reviewed historical documents, newspaper accounts, and existing reports to develop a timeline of what is known about fauna and flora and the timing and use of the springs for irrigation and other purposes. This helps to put the spring systems into context of the larger goal of assessing what it would take to bring Comanche Springs back and to better understand water budgets for the area.

5.1 Pre-Irrigation

Before human intervention, Comanche Springs issued from a series of locations along Comanche Creek, some from a small limestone bluff and others from alluvium (Figure 3.2). Springflows moved down Comanche Creek in a shallow valley and then disappeared into the ground a few miles downstream (Adkins 1927, although this observation was made after irrigation works had been installed, which would have affected downstream flows). Satellite imagery shows an alluvial fan spreading out just beyond the north side of present-day Interstate-10 with a dark-grey discoloration of the landscape (Figure 5.1). Some local residents attribute the discoloration to incineration activities at the landfill located along the creek just north of the interstate; however, the discoloration is seen upstream from the landfill and similar discoloration is seen downstream of Leon Springs, which used to be part of the same flow system seven miles to the west. The discoloration suggests a geochemical process of spring water interacting with the alluvium. If the discoloration is a geochemical process associated with spring chemistry, springs in the area appear to have flowed at least 20 miles downstream.

Springflows would have supported a large wetland system downstream from the springs.[2] A small wetland system exists today at Diamond Y Springs (Van Auken and others 2007), and the Texas Parks and Wildlife Department built an engineered wetland system at San Solomon Springs to approximate the natural system before it was pooled and channelized in the 1930s for recreation and irrigation (Chapman and Bolen 2018; Figure 5.2). Excavations at San Pedro Springs revealed animals from the Pleistocene, during the last ice age some 30,000 to 10,000

[2] A map of the irrigation system in place by 1875 (Figure 5.3) shows a broad area in Comanche Creek referred to as "Laguna de Comanche" stretching from present-day Interstate-10 to at least Sevenmile Mesa.

Figure 5.1: Discoloration of alluvium in Comanche Creek downstream from Comanche (and other) Springs (image from Google 2020).

Figure 5.2: Detail of the artificial ciénega built by Texas Parks and Wildlife Department at San Solomon Springs (photo by Robert Mace, September 14, 2015).

years ago, roamed the area, including mammoths, camels, and sloths (Warnock 1972, Collett 2011).

Captain William Henry Chase Whiting of the U.S. Army noted in 1849 that flow from Comanche Springs held abundant fish and turtles (Justice 2010b) while in 1853 Julius Froebel described catching catfish in Comanche Creek (Ely 2016). In 1853, Julius Froebel noted rushes, reeds, and bogs as well as turtles at Leon Springs (Ely 2016).

Baird and Gerard (1853) provide the earliest scientific description of species in the Fort Stockton area when they described three new species of fish—the Comanche Springs pupfish and the Leon Springs pupfish, collected from their namesake springs, and the Pecos gambusia, from both springs—during the United States and Mexican Boundary Survey (Emory 1857). Hubbs (1978) noted that Mexican tetra had been collected at Leon Springs in 1938.

Van Auken (2007) described plant species in the marshes of Diamond Y Springs including the federally threatened Pecos sunflower, the Leoncita false foxgrove, the federally listed Pecos gambusia, and three rare snail species (*Tryonia circumstriata=stocktonensis*, *Pseudotryonia=Tryonia adamantia*, and *Assiminea pecos*, the latter federally endangered [Ladd 2010]). Echelle and Miller (1974) rediscovered the Leon Springs pupfish at Diamond Y Springs after it was thought extinct (Hubbs 1957, Miller 1961). Leon Springs had been inundated by a small reservoir in 1918 (Hubbs 1978), dosed with the piscicide rotenone in 1947 to kill all the fish in the system to get rid of the carp, (Fort Stockton Pioneer 1947a, Knapp 1953 as referenced by Hubbs 1978), and, ultimately, ceased to flow.

Hubbs (1978) described a variety of species at Diamond Y Springs, some of which may have also lived in Leon and Comanche springs. The Comanche Springs pupfish also lives in Phantom Lake Spring (now supported by pumping from the spring's cave system), San Solomon Spring, Giffin Spring, and East and West Sandia Springs (Winemiller 1997).

San Pedro Springs has evidence of human activity going back nearly 20,000 years (Warnock 1972). Apaches were already invading Jumano territory before the Spaniards arrived in the 1550s (Hickerson 2019), but the acquisition of horses introduced by the Spanish assisted them in driving out or incorporating the Jumanos by the end of the 1600s (Hickerson 2019).

Cabeza de Baca possibly visited the Comanche Springs in 1536 (Brune 1975). Juan Domínguez de Mendoza described six large springs forming Comanche Creek, named them San Juan del Rio, and described buffalo and nut trees at the springs in 1684 (Brune 1975, Collett 2011). Mendoza's journal states that "It is a beautiful plain. In its environs are four high mesa; from the small towards the north flows a spring; within 3 arquebus shots apparently there issue five other springs, all beautiful; and within the distance of half a league a most beautiful river is formed, although without any kind of tree, it having only camalote patches. The water is very clear, although a little alkaline; it is well supplied with fish" (Williams 1924). Mendoza also visited Leon Springs (Handbook of Texas 2010). The Comanches moved into Texas and Apache territory in the 1700s and took advantage of Apache agriculture which provided stationary targets for Comanche attacks (Carlisle 2016).

Once the Comanche wrested control of the West Texas plains from the Apache by the mid-1700s, driving them into the mountains, the Comanche used raiding routes—two that passed through Comanche Springs—to travel deep into Mexico to attack the Spanish, hostilities that continued after Mexico won its independence from Spain in 1821 and Texas won its independence from Mexico in 1836 (Lipscomb 2019). After the United States annexed Texas in 1845, the U.S. Government established a line of forts along the frontier in 1849 (Lipscomb 2019) which was joined by Camp Stockton in 1859 and renamed Fort Stockton the next year (Collett 2011, Wallace 2018). In 1849, Captain William Henry Chase Whiting of the U.S. Army—while mapping out a road from San Antonio to El Paso—called the springs Awache, Comanche for "white [or wide] water" for the wide stream they created in the creek (Justice 2010b). Whiting's interpreter, José Policarpo Rodríguez, claims to have named them Comanche Springs (Justice 2010b).

The U.S. Army established Fort Stockton to protect mail service, travelers, and freighters (Wallace 2018). Due to the importance of the springs as a watering stop, the upper and lower San Antonio-El Paso-San Diego roads, the Butterfield Overland Mail route, the San Antonio-Chihuahua Trail, and the New Mexico Road ran through or near the springs (Wallace 2018). The post was abandoned by federal troops at the beginning of the Civil War in April 1861 and subsequently occupied by Confederate troops before being abandoned again in 1862 (Wallace 2018). In 1867, federal troops re-occupied the fort with a regiment of black troops to protect travelers from the Apache (Wallace 2018).

5.2 Spring Irrigation

Jumano Indians were probably the first to use Comanche Springs as a source of water for irrigation (Brune 1975) and probably irrigated from several springs along Comanche Creek (Collett 2011). Antonio Espejo traveled to the Balmorhea area in 1582 and noted that some fields farmed by the natives (probably Jumanos) were irrigated using diversion ditches (Newcomb 1961 as cited by Simonds 1996). George M. Frazier was the first non-Native American to tap the springs in the area in 1865, capturing part of Leon Springs to irrigate about 200 acres (Fort Stockton Pioneer 1957).

Cesario Torres used flows from Comanche Springs in 1868 to irrigate land belonging to General John Hatch and others (Taylor 1902). By 1870, the U.S. Army was irrigating about 100 acres, mostly as a garden for the post (Taylor 1902). Starting in 1862 and continuing into the 1870s, Peter Gallagher and John James—seeing the potential for irrigation—bought land in the area (Collett 2011), including the abandoned fort, Comanche Springs, San Pedro Springs, and land along Comanche Creek (Williams 1982). Gallagher captured springflow to irrigate alfalfa and other forage crops to support the cattle industry (Jenson and other 2006).

Cesario Torres joined forces with Bernardo Torres and Féliz Garza, obtained land in 1869 and 1870, and dug 2,885 yards of ditches six feet wide and three feet deep fed by a diversion dam they built 0.75 miles downstream from the Comanche Springs (Williams 1982). In 1872 and 1873, they dug another 880 yards of canal (Williams 1982). In 1872, Francis Rooney and Ann McCarthy dug 4,784 yards of ditch and added another 5,200 yards in 1874 (Williams 1982).

By 1875, there were five main irrigation ditches in the area with two fed directly by Comanche Springs, two fed by flows in Comanche Creek, and one fed by San Pedro Springs (Figure 5.3).

In 1875, the legislature passed a bill granting land to canal builders, requiring a minimum of three miles of constructed canals before becoming eligible for land grants (Williams 1982). As a result, Gallagher, M.F. Corbett, and James formed the Comanche Creek Irrigation Company and received a charter to build 24 miles of ditches among five canals (Williams 1982). To protect his water rights, Rooney received a charter under the name of Comanche Irrigation and Manufacturing Company for an existing ditch (Williams 1982). In 1875, Torres and Garza complained that Gallagher, Corbett, James, and A.M. Rector were taking too much water. Rooney filed a lawsuit to prevent Gallagher, Corbett, and James from building one of their canals that he felt would affect his ability to irrigate (Williams 1982). The judge ruled for Gallagher, Corbett, and James; they built the canal; and Rooney's ability to get water was impaired (Williams 1982).

By 1880, several irrigation companies lined Comanche Creek, including the Garza Irrigation and Manufacturing Company (8 miles of main with 6 miles of laterals for 2,000 acres), the Comanche Creek Irrigation Company (12 miles of main with 6 miles of laterals for 4,000 acres), Ditch No. 5 (11 miles of mains with 4 miles of laterals for 3,000 acres), and Ditch No. 4 from San Pedro Springs (6 miles of main with 2 miles of laterals for 1,000 acres) (Fort Stockton Pioneer 1908a). In 1890, E.J. Royal began to irrigate with flows from Leon Springs selling out to H.H. Butz in 1905 (Fort Stockton Pioneer 1957). By 1897, the Rooney Irrigation Company, the Leon Irrigation Company, and the Comanche Irrigation and Manufacturing Company were registered with the state (Mayfield 1897).

By 1900, the Southwest Irrigation Company owned two ditches fed by flows from Comanche Springs: the Garza Ditch and the Comanche Creek Irrigation District ditch, both on the east side of Comanche Creek (Taylor 1902, Figure 5.4). A dam of cottonwood logs and turf diverted water into the Garza Ditch which directed flows six miles to cattle ranches (Taylor 1902) on the north side of Sevenmile Mesa. This dam was located on Comanche Creek between present-day U.S. Highway 385 and U.S. Highway 285 (Williams 1982); remnants of the Garza Ditch can still be seen today on satellite imagery.

The Comanche Creek Irrigation District ditch watered 600 to 800 acres with 400 acres in alfalfa (Taylor 1902). Two ditches on the west side of Comanche Creek—Rooney Ditch A and Rooney Ditch B—were constructed in 1876 and 1877, respectively (Taylor 1902). The two ditches irrigated 1,360 acres in 1900 (900 acres in corn, 400 acres in cotton, and 60 acres in alfalfa) with the ability to irrigate 6,000 acres (Taylor 1902). The Hermosura Ditch, owned by J.H. Crawford at the time, captured flows from San Pedro Spring and irrigated 160 acres (Taylor 1902). The Leon Ditch tapped into Leon Springs to irrigate 260 acres owned by Mrs. Royall (Taylor 1902).

By 1908, the Comanche Creek Irrigation District ditch watered 900 acres of Johnson Grass on 7-D Ranch (with a small return due to "…very slack methods used in irrigation and cultivation"), and James Rooney was irrigating about 700 acres in alfalfa, corn, and fruit (Nagle

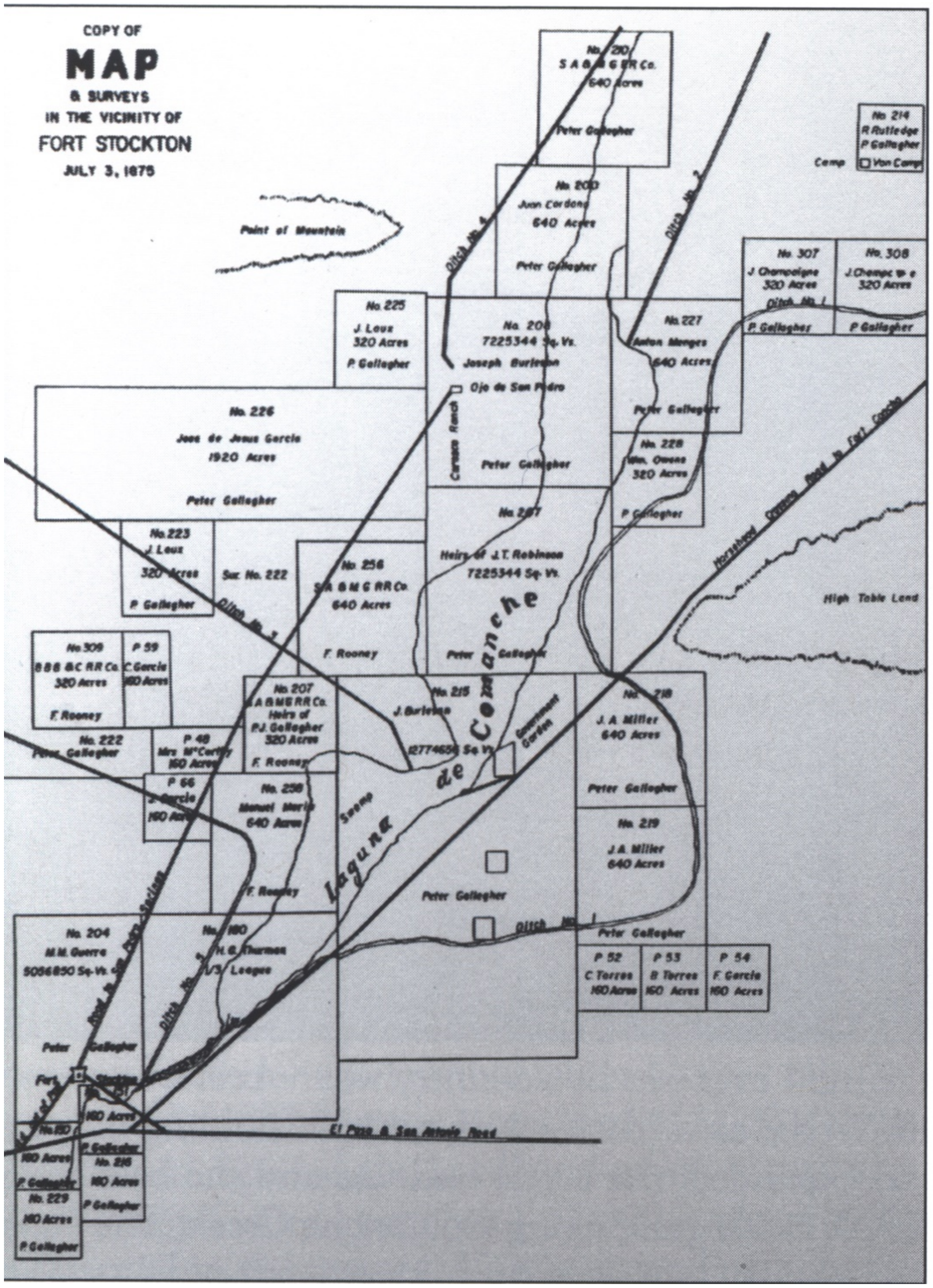


Figure 5.3: A survey from 1875 showing the original irrigation ditches (from Williams 1982). The irrigation system changed substantially by the early 1910s when the system came under the management of the Pecos County Water Control and Improvement District No. 1. A close inspection of satellite imagery reveals remnants of the irrigation canals from 1875.

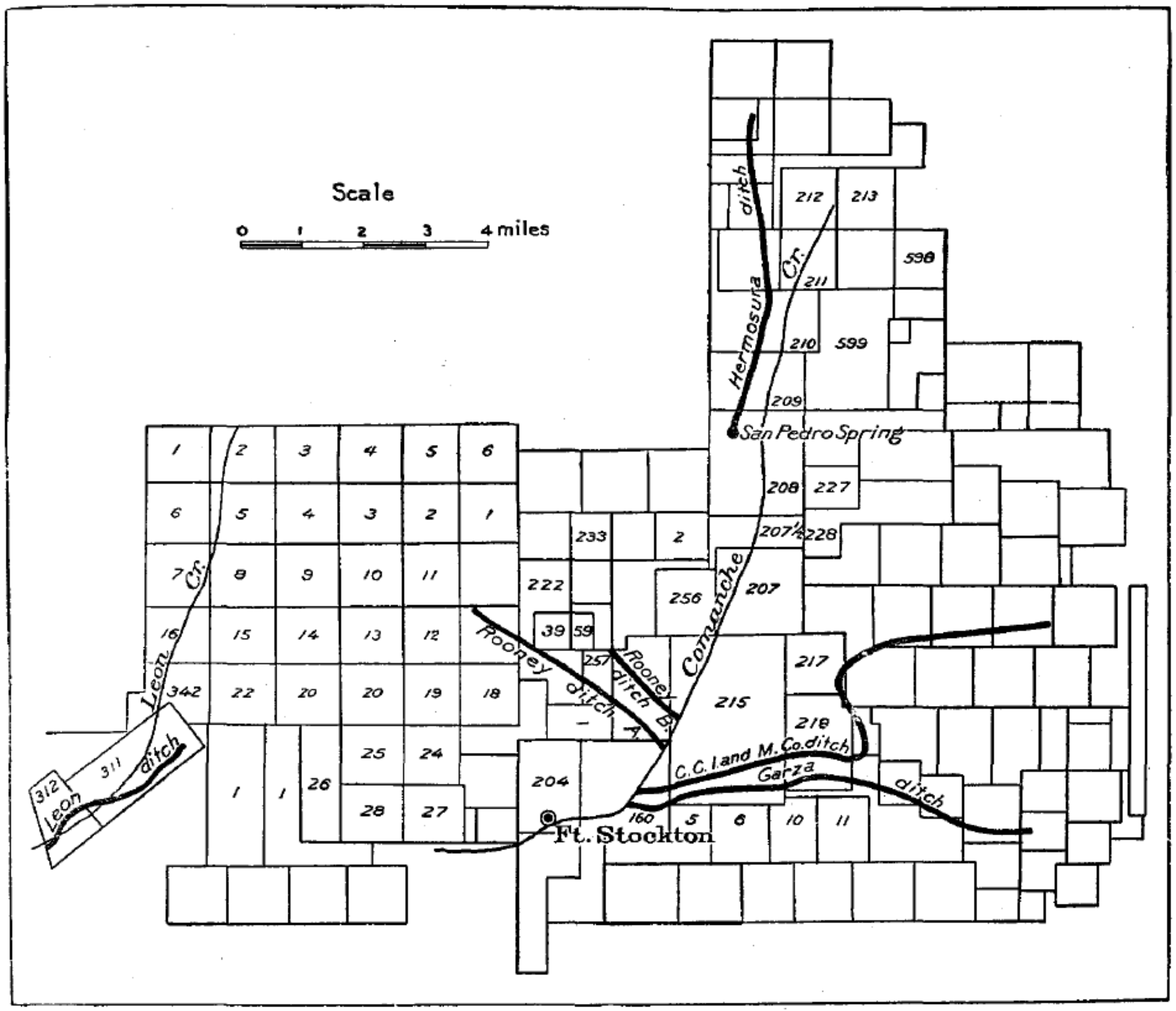


Figure 5.4: Primary irrigation ditches in the Fort Stockton area circa 1902 (from Taylor 1902).

1910). James Crawford irrigated 500 acres of alfalfa, milo maize, and corn from San Pedro Spring (Nagle 1910). By 1913, the full flow of Comanche Springs was used to irrigate about 6,000 acres of cotton, alfalfa, small grains, other feed crops, and small quantities of vegetables (Armstrong and McMillion 1961) and power a gin (Brune 1975, Collett 2011).

Gerald Beeman and J.Y. Webb bought Leon Springs in 1910 and created the Leon Springs Irrigation Company (Collett 2011). Irrigated lands started with small tracks but later came under the single ownership (Carter and others 1928) of R.D. Webb Farms (Dante 1947). The flow from Leon Springs and associated flow-enhancing wells (see Section 5.4 The First Wells) was impounded in 1918 in Leon Lake to provide 6,000 acre-feet of storage for irrigation (Webb 1952 as referenced by USFWS 1980, Hubbs 1978) along Leon Creek north of today's Interstate-10. The lake backed water up to and over the springs by 1920 (Hubbs 1978). The Irrigation Age (1917) noted that state of Texas had granted the Leon Springs Irrigation Company a permit to store and divert 7,540 acre-feet of water a year from Leon Creek for irrigating 3,017 acres (TBWE [1925] shows that the state authorized the Irrigation Company 100 acre-feet per year to irrigate 50 acres on August 1, 1921, suggesting increased appropriations with time).

In 1913, work began by the Fort Stockton Irrigation Company to line the canals from Comanche Springs (Fort Stockton Pioneer 1913a). By 1921, the Pecos County Water Improvement Irrigation District No. 1 had been formed (Fort Stockton Pioneer 1921). The Texas Legislature passed Senate Bill 169 in 1925 which allowed for the creation of water control and improvement districts. Sometime thereafter, the Pecos County Water Improvement Irrigation District No. 1 was renamed the Pecos County Water Control and Improvement District No. 1. It was under the management of the Improvement District that the remnants of the irrigation system seen today were developed, including the diversion dam just east of U.S. Highway 285, the siphon under Comanche Creek just north of present-day Interstate-10, and the canal system downgradient.

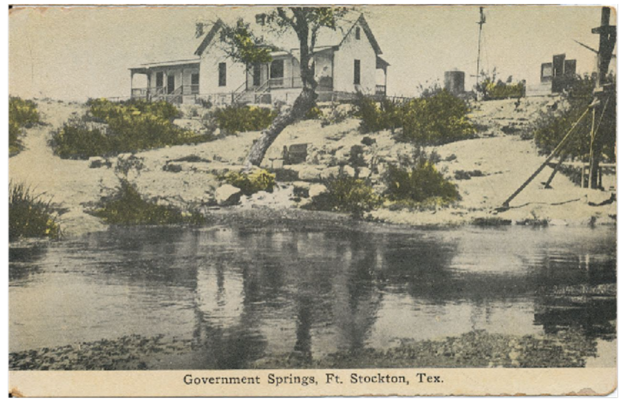
In the end, land developers captured almost all, if not all, of these springs for irrigation projects with irrigation canals slicing through the countryside. By 1913, the full flow of Comanche Springs was used to irrigate about 6,000 acres (Armstrong and McMillion 1961) and power a gin (Brune 1975, Collett 2011). Carter and others (1928) report that farmers irrigated 6,000 acres from Comanche Springs and 3,000 acres from Leon Springs. Leon Springs and a couple wells irrigated about 2,000 acres by 1946 (Armstrong and McMillion 1961). By 1953, 107 families relied on Comanche Springs for their livelihood (Johnson and others 1954).

5.3 Recreation

Swimming in the spring water has been a favorite pastime of locals from the beginning. Early photographs from about 1900 show children and adults alike enjoying the water first in Comanche Creek and then, over time, in a more and more developed swimming hole at Big Chief and Government springs (see, for example, Collett 2011; Figure 5.5) with most of today's bathhouse, pavilion, and pool border installed by 1938 (Justice 2010b). Leon Lake, stocked with fish and with a dance hall nearby, was a favorite spot for people in the area (Collett 2011). The Fort Stockton Country Club was built at Leon Lake in 1927 (Fort Stockton Pioneer 1957).

Fort Stockton started the Water Carnival in 1936 to commemorate Texas' 100th anniversary (Collett 2011). Six carnivals were held annually but were suspended during World War II. After the war, the carnival started again in 1947 (dedicated that year to O.W. Williams [Pollard and Gwin 2011]) before being suspended in 1951 due to decreasing spring flow (Fort Stockton Pioneer 1953e). The Water Carnival returned in 1954—and continues today—after the county built an artificial pool resting on piers above the spring basin (Fort Stockton Pioneer 1954b).

Looking east over Government Springs and Comanche Creek (circa 1910)



Looking west over Comanche Creek and Government Springs (circa 1910)

Looking south over Comanche Creek and the natural pool (1937)

Looking down at the natural pool (circa 1947)

Looking toward the southwest across the natural pool (circa 1947)

Looking toward the southwest across the artificial pool (circa 1955)

Figure 5.5: Evolution of the swimming hole at Big Chief and Government springs (postcards from the personal collection of Robert Mace).

5.4 The First Wells

Shallow wells have probably been sunk in the area since the mid-to-late 1800s for household supply and windmills. Toward the end of the 1800s, there was interest across the state in drilling deep wells to tap into flowing artesian water, the first of which was (unsuccessfully) drilled near the Pecos River close to present-day New Mexico by Captain John Pope between 1855 and 1858 (Smith 2010). It took more than 50 years after that before the first high-volume wells were drilled in the Leon-Belding area for irrigation.

It is unclear exactly when the first irrigation wells were drilled. The Fort Stockton Pioneer (1911c) notes that by 1911 there were already a few farms fed by six flowing artesian wells in the Leon Valley with more on the way. Based on newspaper accounts and local geology, these wells had low yields and were downstream of Leon Springs.

The Leon Springs Irrigation Company incorporated in 1910 (McDonald 1912) and started buying land in Leon Valley in 1911 (Fort Stockton Pioneer 1911d). In late 1912, they bought Leon Springs from the U.S. and Mexican Land Trust Company (Fort Stockton Pioneer 1912) and announced in 1913 that they had big plans for the springs, including a goal of doubling their flow (Fort Stockton Pioneer 1913b). The Company's approach included installing a concrete-lined canal through the springs to lower the water level at the springs 10.5 feet to increase its flow (Fort Stockton Pioneer 1913c, 1914). The canal also drained several large spring-fed ponds; one of the proprietors (L.B. Westermann) captured the affected fish and invited Fort Stockton over for a fish fry (Fort Stockton Pioneer 1914).

The Company drilled its first well near the springs in late October 1915, a well that reached a depth of 320 feet and flowed at about 750 gallons per minute (Fort Stockton Pioneer 1915c; the six wells the Company ultimately at this time ranged in distance from the springs by 400 to 2,300 feet; Figure 5.6). The local newspaper reported that "This well proves beyond a doubt that an untold amount of water can be developed in Leon Valley by going after it" (Fort Stockton Pioneer 1915c). The Company referred to the spring water as "molten silver" (Fort Stockton Pioneer 1915b). In November 1915, the Company announced plans to drill more artesian wells and a reservoir to capture the flow of the springs and the wells (Fort Stockton Pioneer 1915c).

A second well completed in January 1916 produced 2,000,000 gallons a day (about 1,400 gallons per minute) at a depth of only 70 feet, prompting the irrigation company to immediately drill another well (Fort Stockton Pioneer 1916a). A third well with a depth of 56 feet also drilled in January brought the total flow from the three wells to 5,000,000 gallons per day (about 3,500 gallons per minute) and "…had in no way interfered with the already splendid flow from the company's numerous natural artesian springs" (Fort Stockton Pioneer 1916b). In all, the Company reported a total flow of 24.67 cubic feet per second in January, 50 percent more than the natural springs alone (Fort Stockton Pioneer 1916c)[3]. On February 26, 1916, the

[3] A 50 percent increase in flow would put the original flow at Leon Springs proper at 16.5 cubic feet per second (two thirds of 24.67 cubic feet per second). Subtracting reported yields for the three wells results in a springflow about

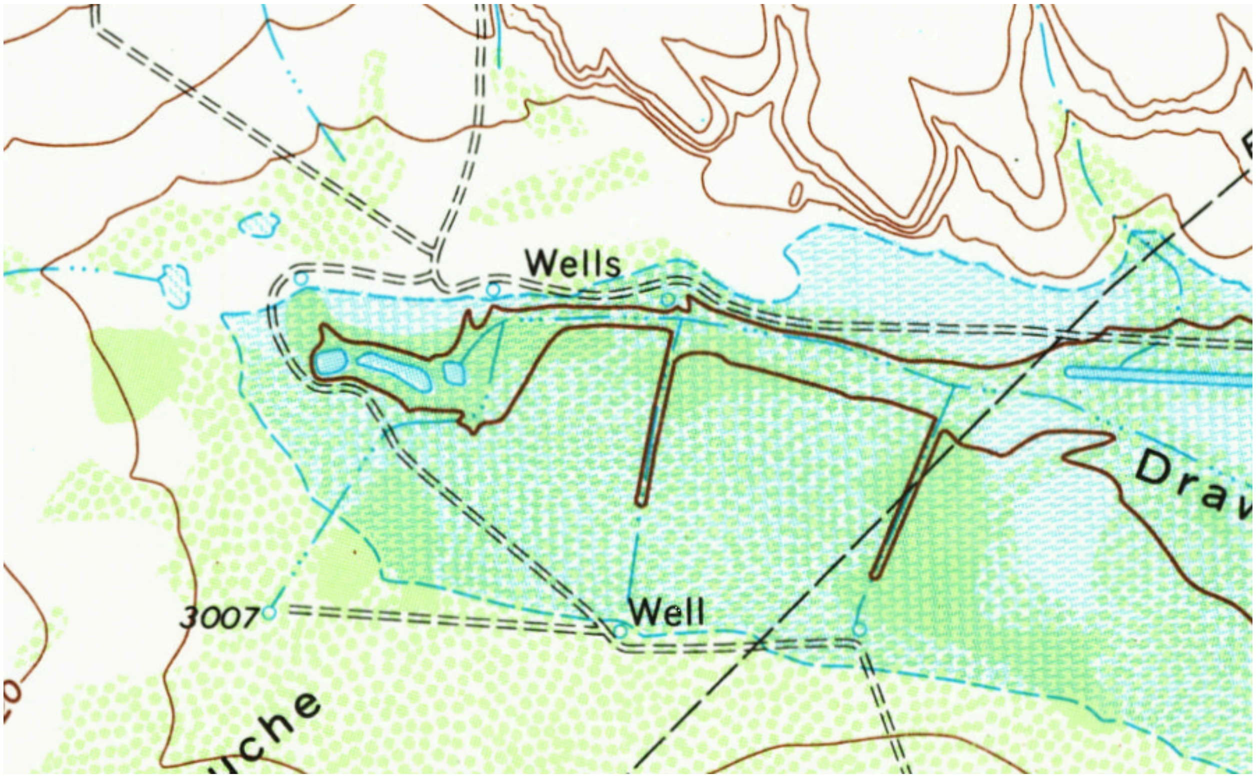


Figure 5.6: Six wells drilled between 1916 and 1917 around Leon Springs by the Leon Springs Irrigation Company (the three small water bodies shown within the footprint of the lake's limits) (from USGS 1970).

Company brought in its fourth well at a depth of 300 feet, and it was "belching Adam's Ale" at the rate of 1,600 gallons per minute (Fort Stockton Pioneer 1916f). In September 1916, the irrigation district completed a fifth well that was 68-feet deep and flowed at 1,740 gallons per minute (Fort Stockton Pioneer 1916d).

In June 1917, the Leon Springs Irrigation Company announced a contract to build a reservoir to store the winter flows of Leon Springs and flood water of Leon Draw (Fort Stockton Pioneer 1917d). In December, the contractor closed the reservoir's gates to begin capturing spring flow (Fort Stockton Pioneer 1917e). At a mile long and 2,000-feet wide, the newspaper reported that "This is the biggest body it has been our pleasure to look upon since our recent visit to the Pacific" (Fort Stockton Pioneer 1918a). In October 1918, the Company let out a contract to drill two more wells at the springs to increase flow (Fort Stockton Pioneer 1918b). The

12.6 cubic feet per second, suggesting that the wells were interfering with springflows and, surely, with each other (which is not in agreement with Fort Stockton Pioneer [1916f], which claimed that "[t]he bringing in of this well, like the three others previously bored has had a tendency to increase the spring flow rather than to decrease it"). This previous calculation is not entirely accurate since each new well would have also probably interfered with the wells drilled before it. The unusual specificity of the flow measurement may be indicative of the engineer the Irrigation Company employed.

irrigation district attempted to drill another water well near the springs in 1923 but hit natural gas instead (Fort Stockton Pioneer 1929; we were not able to find information on the sixth well).

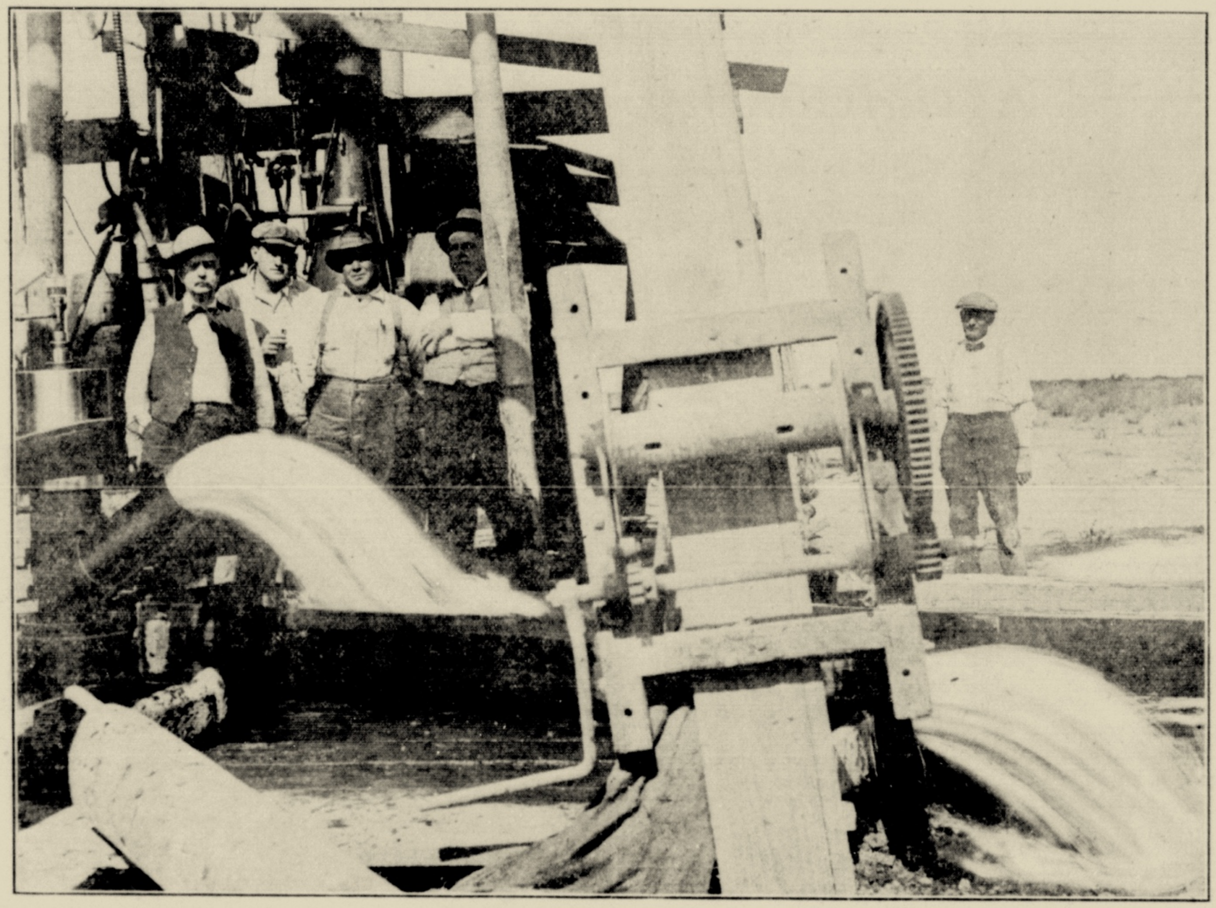
In total, the flow of Leon Springs and its five flow-enhancing wells amount to about 26.5 cubic feet per second (which we get by adjusting the total reported flows of 31 cubic feet per second by the total measured flow reported flows for the first three wells and the springs divided by the total reported flows for the first three wells and the springs).[4] Using a pre-well springflow of 16.5 cubic feet per second (see Footnote 3) results in an increase of flow of about 10 cubic feet per second. The deep canal dug through the springs to lower water levels and increase flow may have added about a cubic foot per second of flow (comparing 16.5 cubic feet per second calculated here with 15.5 reported by Fort Stockton Pioneer 1911a). By 1946, about 2,000 acres were irrigated with Leon Springs and its nearby wells (Armstrong and McMillion 1961).

In an editorial published on June 9, 1922, the Fort Stockton Pioneer noted that, although Pecos County was using "all the water we have," oil prospecting had revealed usable groundwater in the area starting with the artesian Nine-Mile Well drilled on San Pedro Ranch in 1916–1917 to supplement flow to San Pedro Springs (Fort Stockton Pioneer 1922).

5.5 Pumps and Pumping

Perhaps due to the success of the Leon Springs Irrigation Company's well drilling, the Davenport Irrigation Land Associates (Davenport), made up of northern and eastern investors, bought 25,000 acres in the Belding area to plat a townsite, build a hotel, and irrigate and sell land. After finding water at a depth of 323 feet, Davenport planned to drill a well for every quarter section of their holdings (Fort Stockton Pioneer 1916e). In 1917, Davenport used Layne and Bowler to drill the first pumped large-capacity irrigation well in the area, halfway between Leon Springs and the new town of Belding (Fort Stockton Pioneer 1917a, b; Figure 5.7). Layne and Bowler installed a 16-inch centrifugal pump and were able to pump 1,000 gallons per minute from the well (Fort Stockton Pioneer 1917b). The newspaper ribboned the front page with "If the man who makes two blades of grass grow where only one grew before is a public benefactor, what shall we say of the man who digs a well in dry land and pumps water to grow big crops where no crops ever grew before?" (Fort Stockton Pioneer 1917a). At the flowing wellhead, Davenport announced plans to quickly drill more wells (Fort Stockton Pioneer 1917a); however, it appears they went bankrupt before realizing these plans.[5]

[4] Someone smarter than us on well hydraulics needs to do a more sophisticated analysis of this.
[5] It's unclear what happened to the Davenport Irrigation Land Associates. In March of 1917, the District Court awarded John B. Linger and others $11,596.11 from Davenport (Fort Stockton Pioneer 1917c). In March 1918, the paper posted notice that the land and hotel Davenport owned in Belding would be auctioned to pay debt (Fort Stockton Pioneer 1918c; the Davenport Irrigation Land Associates laid out the town of Belding [Justice 2010a]), suggesting they had gone bankrupt. Justice (2010a) suggested that high pumping costs sealed the fate of Belding (and the hotel was moved to Leon Lake).



THE FIRST PUMPED IRRIGATION WELL IN LEON VALLEY—PUMPING OVER 1000 GALLONS OF WATER A MINUTE

Figure 5.7: Photograph of the first pumping well drilled in the Leon-Belding area by the Davenport Irrigation Land Associates (from Fort Stockton Pioneer [1917a])

Fort Stockton began to operate its municipal water system in 1928, using water from wells tapping solution openings in the Comanche Peak limestone (part of the Edwards-Trinity Aquifer) within the city limits (Armstrong and McMillion 1961). The Pecos County Water Improvement Irrigation District No. 1 drilled its first irrigation well in 1939 to supplement flow from Comanche Springs (Armstrong and McMillion 1961). In April 1941, Webb Farms drilled a flowing artesian well west of Lake Leon resulting in 2.75 cubic feet second of additional flow (about 1,200 gallons per minute; Fort Stockton Pioneer 1941).

Well drilling greatly expanded after World War II in Texas due in large part to affordable down-hole pumps and the beginning of the 1950s drought. It was then that landowners began systematically drilling wells south of Leon Springs and finding well yields that could support large-scale irrigation. Most wells in the Leon-Belding area were drilled between 1945 to 1951 and between 1956 to 1957 (Armstrong and McMillion 1961) with the hiatus probably due to uncertainties caused by the subsequent lawsuit. Clayton and J.C. Williams, sons of O.W. Williams, had bought land from eastern investors who had discovered substantial groundwater through test wells (Pollard and Gwin 2011; the eastern investors were most likely Davenport Irrigation Land Associates).

Between 1943 and 1954, farmers also drilled several irrigation wells near Fort Stockton, but the wells were not sustainable through the growing season because water levels dropped below solution channels (Armstrong and McMillion 1961). By 1955, 3,114 acres of cotton were grown in the Leon watershed resulting in an estimate of 20,600 acre-feet of water pumped in the Leon-Belding area (Audsley 1956). A total of 5,409 acres of cotton was allotted in 1956 for the Leon-Belding area (Audsley 1956) suggesting, based on the 1955 numbers, that about 36,000 acre-feet were pumped that year. In 1958, the combined discharge from wells and springs in the Fort Stockton-Leon-Belding area was about 51,000 acre-feet (Armstrong and McMillion 1961).

5.6 Impacts from Groundwater Production

Production from an aquifer—whether through flowing wells or pumping—affects the flow of water in that aquifer. In almost all cases, there is a local decline of water levels around the well that directs groundwater flow toward that well. Two wells may interfere with each other, meaning that their local water-level declines reach out to intersect each other, thus amplifying water-level declines and decreasing well yields. If enough wells are drilled, water-level declines can become regional in scope, affecting water levels and groundwater flow over a larger area, and leading to unsustainable pumping.

Initially, water produced by a well comes from water stored in the aquifer, which is why there is a decline in water level. The water comes from draining the pores in the aquifer or, if the aquifer is under artesian conditions, from compressive storage from decreasing pressure in the aquifer. As production continues, the zone of influence from the production can begin to capture flows that previously went elsewhere, such as to springs, other formations, or other parts of the aquifer.

As early as 1932, the Texas Board of Water Engineers noted, while proposing the drilling of wells in the Balmorhea area to supplement springflow for local irrigation, that "[t]here is, however, a danger that the drilling of many artesian wells and the extensive utilization of the water from them may seriously decrease the flow of the large sprints [sic; should be springs] near Balmorhea and Fort Stockton, on which the irrigation districts in these localities depend" (TBWE 1932).[6]

For our analysis, we divided the effects of production on the aquifer and springs in the study area into three periods: pre-1935, 1935 through 1947, and post-1947.

[6] This does not mean the Texas Board of Water Engineers thought that pumping in the Leon-Belding area would impact springflow in Comanche Springs. The most logical conclusion at that time would have been that pumping in the Leon-Belding area would have impacted Leon Springs (something that was probably noticed when six wells were drilled around it). In later years, reflecting on the impacts of pumping in the Leon-Belding area on Comanche Springs, Clayton Williams said "I had no idea that [the wells] would dry up the creek. I thought that it might weaken a little bit, but I had no idea." (Pollard and Gwin 2011).

5.6.1 pre-1935

In all, between 1915 and 1920, the Leon Springs Irrigation Company drilled six flowing wells at the springs to increase discharge for irrigation (Armstrong and McMillion 1961; it may be that only five of the six were successful since the sixth came in with natural gas). As shown previously, Leon Springs and its five flow-enhancing wells probably produced about 26.5 cubic feet per second. Brune (1975) reported flow at Leon Springs (which included flow from the flowing wells) averaging 23 cubic feet per second in water year 1920, 16 cubic feet per second in water year 1932, 18 cubic feet per second in water year 1933, and 14 cubic feet per second in water year 1946. White and Meinzer (1931) report that Leon Springs and the flow from "eight or nine artesian wells" was between 22 and 31 cubic feet per second. Variations in flow could have been due to seasonal or year-to-year variations in the local component of recharge; however, newspaper accounts suggest that the silting of spring orifices from flood flows down Acebuche Draw also impacted spring flows (Fort Stockton Pioneer 1947b).

After flow increased at Leon Springs, flow decreased at Comanche Springs. The U.S. Geological Survey measured flow at Comanche Springs at 66 cubic feet per second in summer 1899 and 64 cubic feet per second in July 26, 1904 (Atkins 1927) before dropping to 45 cubic feet per second by 1919 (Brune 1975), about a 20 cubic feet per second drop in flow. After 1919, flows at Comanche Springs stayed within 10 percent of 45 cubic feet per second until 1947 (based on data presented in Brune 1981).

Previous authors have noted that the drop in measured springflow is unexplained (for example, Small and Ozuna 1993). However, as we have shown in the previous section, flows at Leon Springs were enhanced, which would have captured flows previously bound for Comanche Springs. Sharp and others (2003) suggested that the pre-1940s decrease was due to a longer-term drying of the region; however, they were not aware of the flow-enhancing wells drilled near Leon Springs (not to mentioned that the rate of springflow decline was too steep to be due to long-term drying). Ely (2016) stated that decreased springflow was due to pumping between 1923 and 1947; however, as shown, flow declined at Comanche Springs before 1923.

Given what we know today about the flow system, the timing of well construction and production, and the timing of decreased flows at Comanche Springs, the wells drilled to enhance flows at Leon Springs almost assuredly caused decreased flows at Comanche Springs.

5.6.2 1935 through 1947

Flows at Comanche Springs remained relatively steady from 1912 through 1935 and then began to slowly decrease through 1947 from about 46 cubic feet per second to about 40 cubic feet per second. By the mid-1940s, other wells had been drilled in the Leon-Belding area (Dante 1947), including (well name; year drilled; depth; owner; yield; use):

- E-27; 1939; 1,550 feet deep; R.D. Webb Farms; flows at 2,500 gallons per minute (probably from the Capitan Reef Aquifer); used for irrigation
- E-28; 1943; 500 feet deep; Clayton Williams; flows from Rustler; used for irrigation

- E-29; 1946; 446 feet deep; Clayton Williams; can produce at least 2,500 gallons per minute (probably from the Rustler); used for irrigation
- E-30; 1940; 1,756 feet deep; R.D. Webb Farms; flowed at 1,500 to 1,800 gallons per minute in 1946 (probably from the Capitan Reef Aquifer); used for irrigation
- E-31; unknown drill date; 3,575 feet deep; C.L. Thompson; flowed 800 gallons per minute (unknown formation); oil test well used for irrigation

None of these wells were completed in the Edwards-Trinity Aquifer (although there is the possibility they were also completed in the Edwards-Trinity Aquifer); however, given the connectivity between the Capitan Reef, Rustler, and Edwards-Trinity aquifers, pumping from the deeper formations could have an impact on flows into and through the Edwards-Trinity Aquifer. In total, the wells above could produce about 16 cubic feet per second from the subsurface. This production from deeper formations also complicates estimates of groundwater use for irrigation from the Edwards-Trinity Aquifer.

5.6.3 post-1947

Most wells in the Leon-Belding area were drilled between 1945 to 1951 and between 1956 to 1957 (Armstrong and McMillion 1961). M.C. Slaton opened the first irrigation project in the area, later joined by Bill Cochran and T.B. Armentrout (Fort Stockton Pioneer 1951g). By 1955, the Leon-Belding Irrigation Area supported 3,114 acres of cotton; by 1956, allotments were up to 5,409 acres (Audsley 1956).

As the number of producing wells increased, flows at Comanche Springs (Figure 5.8) and San Pedro Springs (Figure 5.9) also decreased, with springflows showing the seasonality of irrigation pumping with a year-on-year decline in winter-month flows. Water levels in the Leon-Belding Irrigation Area also decreased with increased pumping (Figure 5.10). Complicating the interpretation at the time was the beginning of the drought of the 1950s from 1947 to 1955, which also correlates with decreased springflows (Audsley 1956).[7] However, the sudden amplified seasonality of springflows—not observed earlier, the direct correlation with increased pumping, and the absence of springflow after the drought ended all suggest pumping impacted spring flows, not drought. Later studies confirmed this connection (Armstrong and McMillion 1961, Small and Ozuna 1993, among others).

[7] Some residents continue to blame the 1950s drought for the loss of the springs. Audsley (1956) probably didn't help matters with this statement: "Although the correlation between spring discharge and precipitation is partly masked by the effects of pumping, the overall decline of discharge of the springs that started in 1947 can be correlated with the period of subnormal rainfall from 1947 through 1955." While a factual statement (he was probably trying to note whether there was a climatic signal to spring flow), it may leave a reader with the impression that drought dried up the springs. Some other residents assign blame to an earthquake or earthquakes changing the plumbing (Trans-Pecos Texas is the most naturally seismically active part of the state); however, the return of springflows and the correlation with pumping suggests earthquakes are not to blame.

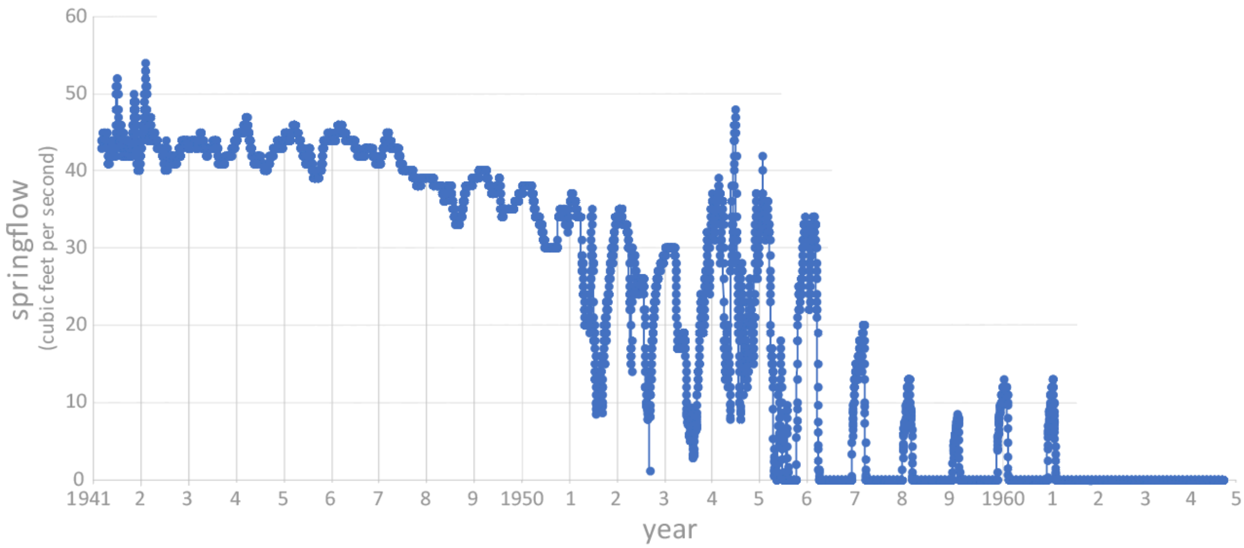


Figure 5.8: Springflow at Comanche Springs from 1941 to 1965 (data from USGS 2020a).

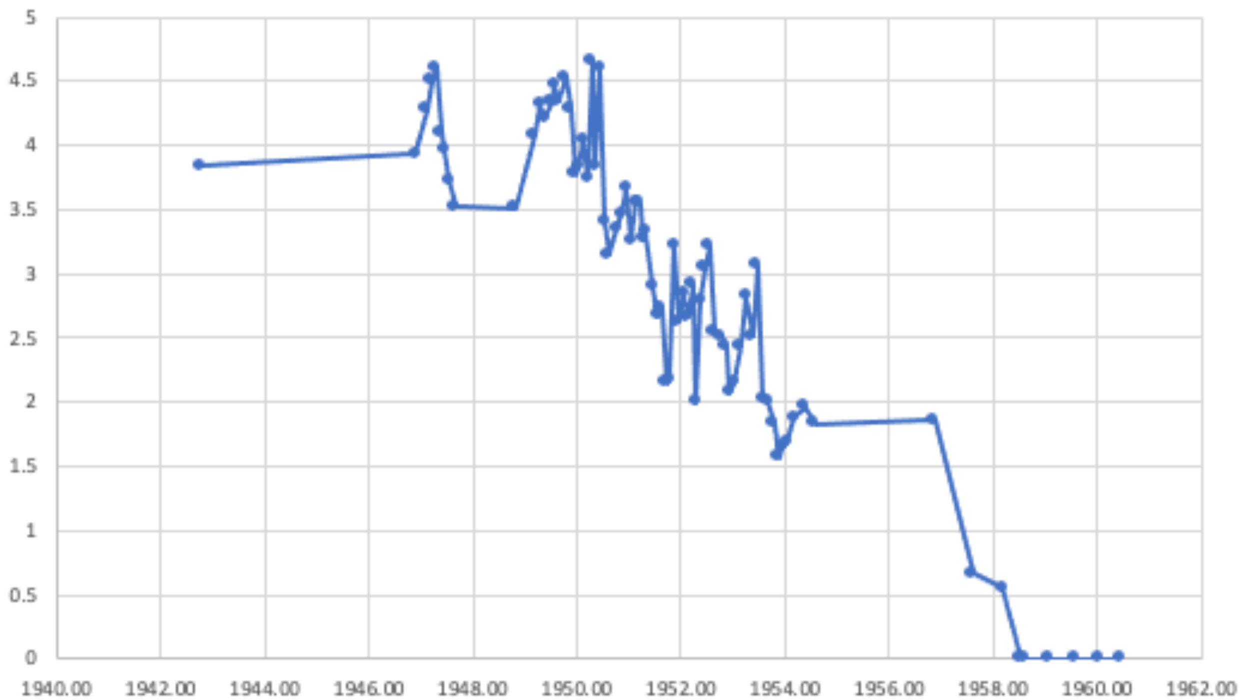


Figure 5.9: Spring flow at San Pedro Spring (data from Parker and others [1950a, 1950b, 1951, 1952, 1953] and Wells and others [1954, 1955, 1956, 1958, 1959, 1960]; missing data from Parker and others [1950b] due to page being cut off in scan).

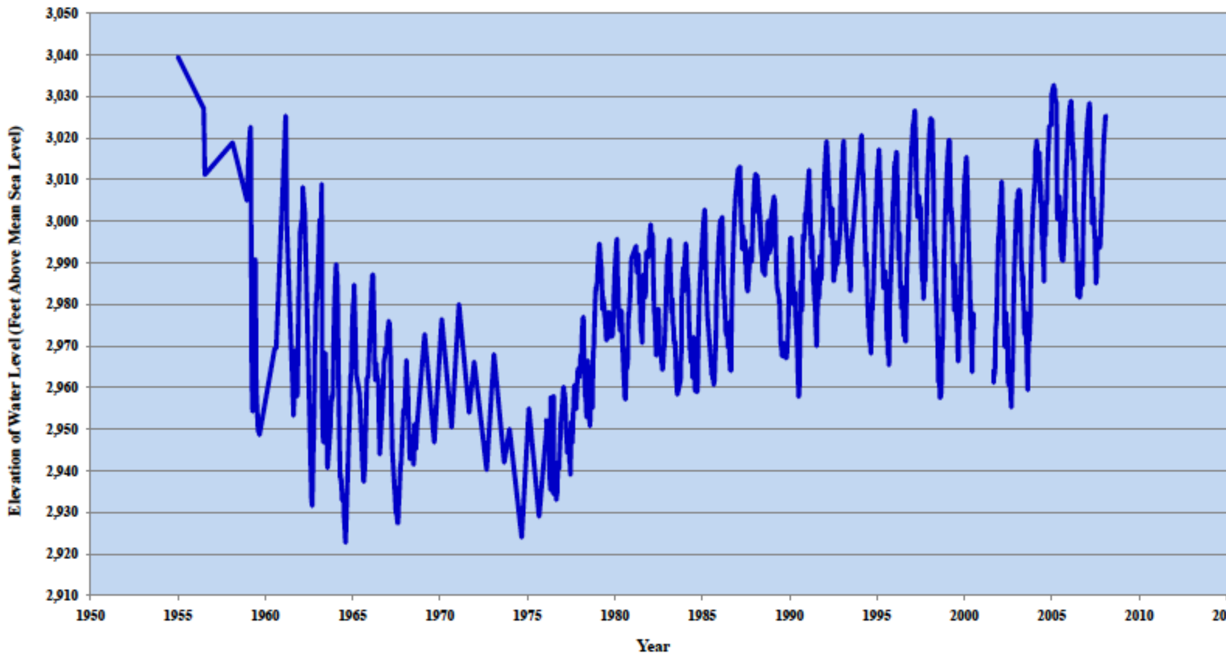


Figure 5.10: Composite hydrograph from wells in the Leon-Belding Irrigation Area adjusted to Well 52-16-802 (from Harden and others [2011, their Exhibit 47 in their Appendix D]).

Problems with Comanche Springs started in the summer of 1950 (Kerrville Times 1951), with the local paper placing blame with the drought (Fort Stockton Pioneer 1951a). With only 25 percent of normal flow at winter's midpoint[8] and as flow in Comanche Springs declined in 1951—drying up the upper springs by April—the Pecos County Water Control and Improvement District No. 1 temporarily closed the pool to look at ways to increase flow by injecting air into the Big Chief Spring (Fort Stockton Pioneer 1951a). In May, the Improvement District installed pumps to lower the water level at the springs to induce more flow (Fort Stockton Pioneer 1951b). In June, the Improvement District tested four 4,500 gallons per minute pumps with 12-inch flow lines, but the test was inconclusive due to runoff from recent rains (Fort Stockton Pioneer 1951c). Because pumping was going to impact the pool, the county and city began to investigate constructing a pool in the spring basin and pumping spring water into it as well as investigating building a city pool at a new site (Fort Stockton Pioneer 1951e). By July, citizens of Fort Stockton were asked to conserve water to help the irrigators (Fort Stockton Pioneer 1951e).

By August, the Improvement District had drilled two wells in the immediate vicinity of Big Chief to supplement flow (Kerrville Times 1951). The springs "…ceased abruptly…when two new well pumps went to work…" on August 11, 1951 (Kerrville Time 1951) pumping 8,200

[8] Flow data for the spring system from the U.S. Geological Survey does not agree with this statement; it may refer to flows from the upper springs.

gallons per minute (Fort Stockton Pioneer 1951f). Rather than water flowing from the spring, water—including pumped water—went down into the spring (Kerrville Times 1951), reversing the flow. Another well was under construction at Government Springs[9] with a fourth well planned (Fort Stockton Pioneer 1951f). Except for a period after the wells were struck by lightning (Big Spring Herald 1951), the springs had no flow until the wells stopped pumping in early October (Fort Stockton Pioneer 1952a).[10]

The pool opened for swim season in early May of 1952 (Fort Stockton Pioneer 1952b), but ever-decreasing flows greeted swimmers and spring irrigators again. In August, the Improvement District "…cited the decreased flow of the Springs as a serious economic problem to its landowners, a tragedy to the citizens of the county in general because it has deprived them of the wonderful recreation spot enjoyed for so many years, and as a threat to public health of the city of Fort Stockton by the creation of stagnant and polluted waters" (Fort Stockton Pioneer 1952c). The Improvement District proposed lining the canals with concrete, building a flood control dam upstream of the park, and drilling a well for a pool (Fort Stockton Pioneer 1952c). With decreased flows, especially during peak irrigation season in the Leon-Belding Irrigation Area, downspring irrigators shifted to feed crops and winter grazing crops to use limited water supplies (Fort Stockton Pioneer 1952d) as well as field leveling to increase efficiency and yield (Fort Stockton Pioneer 1952e).

In October of 1952, a bond election approved $190,000 of funds for a concrete basin and water-control system for the pool, straightening and lining the canals and flood-water channels through the park, and building an earthen flood-control dam above the park (Fort Stockton Pioneer 1952f). Silliman and Walker, Lee Hunter Planning Services, and Paddock Engineering Co. of Texas (pool engineers) engineered the projects with the pool designed to accept flow from the springs, pumped water from the springs, or water from an alternative source (Fort Stockton Pioneer 1952g). The straightened and lined canals were designed to address stagnant water issues (Fort Stockton Pioneer 1952g).

5.6.4 Decreasing Flows, Increasing Tensions, and a Lawsuit

In December of 1952, the Improvement District hired Hart Johnson and, under the names of the district's elected directors (Willie Hoefs, Sim Reeves, Paul Crone, Roland Warnock, and Frank Fulk), filed a lawsuit in the 83rd District Court against various groundwater irrigators in the Leon-Belding Irrigation Area and to the south of the springs (Fort Stockton Pioneer 1952h). The lawsuit initially named, in order, Clayton W. Williams[11]; T.B. Armentrout; Page E.

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[9] The Fort Stockton Pioneer referred to this spring as Little Chief Spring.

[10] Gaging data from the U.S. Geological Survey doesn't show the springs going dry until 1955 suggesting that their measurement point was downstream of the springs and the pumps.

[11] Clayton Williams, Sr., in specific, and the Williams Family, in general, are often solely blamed for the fate of Comanche Springs (see, for example, Freedman 1990, Patoski 2010, Mueller 2011, Beauvais 2017); however, as noted, there were 24 defendants, 18 of which produced or used groundwater for irrigation, and 61 special defendants named in the lawsuit. Clayton Williams, Sr. and his brother irrigated the largest amount of land at the time, which may be why Clayton tops the lawsuit (although his brother was listed alphabetically with the other individually named defendants). More likely, Clayton Williams was listed first because he was prominent in the community

Carson; W.R. Cochran; Loyd L. Davis; M.R. Gonzales; Oscar H. Graham; Thurman Simmons; William Slaton; L.A. Taliaferro; Viola Dullnig Teitsch, and W.J. York, residents of Pecos County; C.G. Teitsch of Dimmit County; H.M. Newham and H.S. Whittenberg of Midland; A.J. Keith of Hidalgo County; W.H. Dullnig of Sutton County; M.C. Slaten of the State of Oregon; J.C. Williams of New York; Anderson, Clayton, & Company of Harris County; Federal Land Bank of Houston; Leon Land & Cattle Company of Hidalgo County; Mutual Life Insurance Company of New York; and National Life & Accident Company of Nashville, Tennessee (by the time of the ruling, Carson; Graham; Dullnig; and Anderson, Clayton, & Company had been dropped as defendants from the lawsuit and E.L. Brown, City of Fort Stockton, Luther C. Holladay, H.M. Newham, Dow Puckett, Thurman Simmons, and D.N. Whittenburg had been added as well as 61 special defendants [Appendix B]).

The lawsuit noted the following users and uses of pumped groundwater:

- Clayton Williams and his brother, J.C. Williams, with two wells and a third on the way to irrigate about 400 acres
- Lloyd Davis with four wells to irrigate 320 acres.
- W.R. Cochran with one well to irrigate about 240 acres
- T.B. Armentrout with one well to irrigate "some land"
- M.C. Slaten with two wells to irrigate his own land of 60 acres and lands owned by William Slaton, W.J. York, and L.A. Talisferro, each with 100 acres
- H. S. and D.R. Whittenburg and H. M. Newnham with one well to irrigate their land
- Dow Puckett with one well to irrigate about 130 acres
- M.R. Gonzales with one well to irrigate about 30 acres
- Viola Dullnig Teitsch Howard., C.G. Teitsch, and W.H. Dullnig with one well to irrigate about 90 acres
- Leon Land & Cattle Company with five wells for irrigation
- E.L. Brown with one well

In the fifth amended original petition (the version the court ultimately considered; Johnson and Montague 1953), the Improvement District argued that the defendants had drilled and pumped wells that "…have penetrated certain well defined and well known underground water channels supplying Comanche Creek with water and have intercepted and interferred [sic] with the passage of such water to the springs of Comanche Creek…" The Improvement District estimated the value of the impacted farmland and improvements at "…close to four million dollars…" (38.7 million in 2019 dollars[12]) due to the capture and conveyance of flows from Comanche Springs and the value of the canal system at half a million dollars (4.8 million in 2019 dollars[13]). The Improvement District noted that, at the time of filing, the springs were going dry for four months during the growing season, recovered to only half of normal flow in the winter, and, if pumping continued, would completely go dry and return the irrigated lands

since he was a long-time county commissioner and a successful businessman, and the Williams Family was also prominent (his father, O.W. Williams, was the county judge at one time as well as a local historian).

[12] https://data.bls.gov/cgi-bin/cpicalc.pl?cost1=4000000&year1=195206&year2=202004

[13] https://data.bls.gov/cgi-bin/cpicalc.pl?cost1=500000&year1=195206&year2=202004

to desert. The petition identified 108 separate owners of land and 273 people in 102 homes within the irrigation district's boundaries.

The petition noted that the springs of Comanche Creek were fed by an aquifer composed of "…well defined and well known channels in which the water flows generally from the Southwest to the Northeast…" and that the defendants had drilled into these well-defined channels. The petition alleged that the groundwater irrigators had no legal right to pump water from these channels because the Improvement District owned all the water, including the water in the underground channels, leading to the springs. The Improvement District made this argument because they believed that the state appropriated them "…all of the surface waters and underground waters feeding Comanche Creek in the years 1913 and 1914…". The Improvement District also argued that, because Comanche Creek was navigable, the source of water to the creek remained the property of the state. The Improvement District asked the court to appoint a Test Master to study the connection between the wells and the spring, prevent the drilling of new wells during the suit, grant the district rights to the source waters to Comanche Springs, and permanently prevent landowners from intercepting flows to the springs.

The groundwater pumpers, in their third amended answer of defendants (the version the court ultimately considered; Looney and others 1953) noted that the Improvement District's claims to groundwater beneath their land as "…contrary to the law of this State…" noting that "…under both the case law of this State, as declared by the Supreme Court of' Texas, and the statutory law, as enacted by the Legislature, the subterranean ground waters in and under one's land belong to the owner of' the land, and the owner or the land may dig thereon, obtain water, capture same, and apply all that is there found by capture to his own purposes, at his free will and pleasure, and if, in the exercise of such right, he intercepts or drains off the water collected from the underground by a spring on adjoining or other land, or a spring far removed, as plaintiff's allegations show here, it is nevertheless damage without injury, and cannot become the grounds of an action." The groundwater pumpers also noted that "…under the laws of the State of Texas subterranean ground waters of every type and character are not subject to appropriation, have never been subject to appropriation, and are not now subject to appropriation".

In May 1953, a Pecos County health officer warned downspring irrigators of health risks of using canal water for domestic use due to low flow unless boiled noting that "A number of families depend on water from the canal for their domestic supplies" (Fort Stockton Pioneer 1953a). In July, wells at Big Chief and Government springs were pumped to stop flow to allow A.P. Kasch and Son to construct the swimming pool (Fort Stockton Pioneer 1953b). "Comanche Springs was an empty crevice this week, and the famous natural pool was a drying mess of weeds and moss, with a few minnows left in small pools after pumps had diverted water flow from the famous Comanche Chief spring and others nearby" (Fort Stockton Pioneer 1953c).

Depositions for the district court case were taken from defendants Clayton W. Williams, L.L. Davis, M.R. Gonzales, Luther C. Holladay, L.T. Magnum, Edward Niemann, M.O. Swafford, L.A. Taliaferro, D.R. Whittenburg, and W.J. York on July 9, 1953 (Fort Stockton Pioneer

1953d). The defendants asked the court to include other landowners noting that 42 wells being used to irrigate were not part of the lawsuit (Fort Stockton Pioneer 1953d). In response, the judge asked the Improvement District to make parties of all who "own any interest in land upon which there are any water wells the water from which is used for purposes other than for household, domestic and livestock purposes, within the boundaries of the area designated by the plaintiff as 'Comanche Creek Watershed'" (Fort Stockton Pioneer, 1953f).

In a two-page decision delivered on September 9, 1953, the district court, through Judge Epperson (1953), ruled against the Improvement District. The district immediately appealed the decision (Fort Stockton Pioneer 1953g). Oral arguments for the Improvement District's appeal of the district court decision were held April 1, 1954 (Pollard and Gwin 2011).

On April 15th, the new swimming pool opened to the public with a single admission price of 35 cents (Fort Stockton Pioneer 1954a). With the new swimming pool in place, the Water Carnival was brought back and held on June 10th through 12th (Fort Stockton Pioneer 1954b).

One July 21, 1954, Judge Alan R. Fraser, on behalf of the appeals court, ruled for the groundwater irrigators, upholding the district court decision (Johnson and others 1954). The Improvement District announced plans to file a motion of rehearing and, if denied, to appeal to the Texas Supreme Court, "It has been a generally accepted fact here since the suit was begun 19 months ago that it would eventually end in the Supreme Court" (Fort Stockton Pioneer 1954c). In his decision, Judge Fraser noted that:

- The Improvement District had "enjoyed the water of Comanche Springs for some ninety years."
- The Improvement District was "…asking the trial court to enjoin said defendants from interfering with the normal flow of Comanche Springs, Pecos County, Texas, except for use by the city of Fort Stockton…"
- The Improvement District "…also claims title to said waters by limitation and prescription, and further in the alternative pleads for correlative rights therein…"
- "It seems clear to us that percolating or diffused and percolating waters belong to the landowner, and may be used by him at his will."
- "We do not find any authority in the courts or the statutes authorizing plaintiff to extend its appropriation, if any it has, to underground waters."
- "In the Cantwell v. Zinser case, supra, defendant's well dried up Spicewood Springs in Travis County, and yet the case was sent back to determine whether the source of the spring water was percolating water or a well defined underground channel."
- "We have as far as possible assumed the allegations of [the Improvement District's] petition to be true. It may be that the answer to this unhappy situation is legislative."

In December 1954, the Improvement District asked the Texas Board of Water Engineers to build a 700-acre-foot dam on Comanche Creek (Brownsville Herald 1954). A permit hearing was held, but there was opposition from two Cameron County water districts (Brownsville Herald 1954).

The Improvement District filed a 109-page appeal to the Texas Supreme Court on October 29, 1954. The groundwater irrigators filed their response on November 29th. On January 26, 1955, the Texas Supreme Court unceremoniously stamped the Improvement District's appeal with "REFUSED—NO REVERSABLE ERROR", allowing the appeal court's ruling to stand. On February 9th, the Improvement District filed a motion for rehearing, stating, in part, that if the groundwater irrigators could legally divert the source of a spring or stream that "…any person who owns land twenty feet from the banks of Comanche Creek can accomplish the same result and the effect is simply to say that the appropriation statutes of the State of Texas are worthless" and that "[i]f petitioner and the 107 landowners in its water district can be deprived of their hard won and long used appropriated rights on any such technicality, then the constitutional amendment and the statutory enactments under it are mere scraps of paper, and strangely enough, the defendants in this case are in the same position as the petitioner. The rights that seem to have been accorded to them because of their geographical position can be destroyed by others who have a more favorable geographical position, because they can never establish any permanent, appropriative or other rights to the water in question."

Nevertheless, the Texas Supreme Court quickly overruled the Improvement District's motion for rehearing on March 15th, thus closing the legal battle over groundwater pumping and the springs. The Fort Stockton Pioneer (1955) reported that "The famous Pecos County water suit is officially ended" and that "Since the January ruling of the court, and the probability that the action of the court would soon become final, there has been a tremendous increase in amount of new land being prepared for irrigation in the region southwest of Fort Stockton and the area south of Leon Lake farms" (Fort Stockton Pioneer 1955).

5.6.5 Low Flow to No Flow, Declining Water Levels

During the 1955 irrigation season, flow at Comanche Springs stopped for 90 days (Armstrong and McMillion, 1961). Fort Stockton's wells inside the city limits saw water levels decline 50 feet between 1953 and 1955 (Armstrong and McMillion 1961). These declines, along with decreasing water quality, caused the city to abandon its Edwards wells and drill deeper into the Trinity sands (Audsley 1956, Armstrong and McMillion 1961).

In March 1956, the State Water Resources Committee held a hearing to discuss the conflict from both sides with Hart Johnson representing the Improvement District and Charles Mathews representing the groundwater irrigators (The Odessa American 1956a). The Improvement District "…hoped they might suggest some form of legislation to protect their water supply" (The Odessa American 1956a). In September 1956, Pecos County voted to fund half the cost of a groundwater survey by the Texas Board of Water Engineers (Fort Stockton Pioneer 1956).

As flow at Comanche Springs continued to decrease, the Improvement District and its individual irrigators drilled more and more wells to compensate, drilling and pumping about 50 wells in the Improvement District's boundaries by 1958 when irrigated acreage had declined to 3,000 acres (Armstrong and McMillion 1961). Unfortunately, groundwater within the Improvement District was from the less productive Trinity with total dissolved solids that ranged from 1,650 parts per million in the southern part to 3,420 parts per million in the northern part (Armstrong and McMillion 1961). As the amount of pumping increased in the Leon-Belding Irrigation Area, San Pedro Springs stopped flowing in April 1958 (Armstrong and McMillion 1961). Leon Lake, fed by Leon Springs, also went dry in 1958 (Mulder 2015a).

In 1958, pumping in the Leon-Belding Irrigation Area drew water levels below the productive zone (Armstrong and McMillion 1961), affecting the productivity of some irrigation wells. Wells yields in some wells started the irrigation season in March at 2,000 gallons per minute and ended in July at less than 1,000 gallons per minute while in others decreased from 1,500 gallons per minute to 150 gallons per minute (Armstrong and McMillion 1961). Continued pumping resulted in overall declines in water levels of 4 feet per year between the winter of 1954–55 to the winter of 1958–59 with annual end-of-irrigation season water levels declining by 40 feet per year (Armstrong and McMillion 1961). In other words, groundwater pumping in the area was exceeding inflows and was resulting in systematic year-on-year water-level declines.

This decrease in water levels and well yields was not sustainable, resulting in the survival of the fittest wells, generally wells located in favorable geology with the most downthrown blocks of the Edwards-Trinity Aquifer. Even by 1960, irrigated farms in the Leon-Belding Irrigation District with less ideal hydrogeology had gone bust (Armstrong and McMillion 1961) with abandoned fields and canals still visible today[14].

As a result of decreasing yields and failing farms, groundwater irrigators formed the Leon-Belding Water Conservation Association to promote the construction of concrete-lined ditches, prevent excessive tailwater, institute more efficient irrigation techniques, and develop other sources of water such as the Rustler Aquifer (Armstrong and McMillion 1961). Indeed, farmers drilled deeper into the Rustler Aquifer to supplement the decreasing yields of the Edwards-Trinity Aquifer (Rees and Buckner 1980).

By 1959, decreased flow from Comanche Springs had reduced irrigated acreage in the Improvement District northeast of Fort Stockton to 500 acres (McGuinness 1963).

In an editorial published on June 11, 1959, the Fort Stockton Pioneer (1959a) stated that "Fort Stockton has had enough fighting because of water and the unfortunate scarcity of that vital commodity in this land." The editorial also referred to a hearing on a State Board of Water Engineers' study (later published as Armstrong and McMillion 1961) and noted that "The hearing is not a rehash of the court battle of a few years ago over who, if anybody, dried up Comanche Springs."

[14] Darrel Peckham, a hydrogeologic consultant to Fort Stockton Holdings, attributed the decrease in agricultural production in the area to increased fuel costs during the 1973–1974 oil embargo (Mulder 2015). TBWE (1981) noted that groundwater irrigation in Pecos and Reeves counties thrived until 1976 and 1977 when rising fuel costs left fallow fields and abandoned concrete-lined canals. An earlier, perhaps more important factor, was that, starting in 1958, pumping began lowering water levels below the productive zone for some wells in the Edwards (Armstrong and McMillion 1961), affecting irrigated farms not located over the deeper, downthrown blocks of the aquifer.

In June 1959, the Fort Stockton Pioneer (1959b) noted that the Board of Water Engineers was deciding whether to designate of an underground reservoir in the area. Designating an underground reservoir was the first step at that time to form a groundwater conservation district since a district had to conform to the boundaries of an underground reservoir (TNRCC 1997). Later that year, the Board of Water Engineers designated Subdivision No. 1 of the Pecos Underground Water Reservoir (TNRCC 1997).

After the winter of 1961–1962, the springs completely stopped flowing (Figure 5.8) and would not be seen again for decades.

6.0 The Return of the Springs

In October 1986, after several weeks of record or near-record rainfall in the area and a decrease in pumping (Freedman 1990), Comanche Springs flowed again for the first time since 1961 (Dearen 1993, Small and Ozuna 1993). Serendipitously, 1986 was also the 50th anniversary of the Water Carnival (Sibley 2013) as well as the 100th anniversary of the military closure of Fort Stockton (Cox 2011).

After the springs came alive, "Fort Stockton City Councilman Oscar Gonzalez and others argued the town should invest its money in revitalizing Comanche Springs. Perhaps Fort Stockton could become something more than a truck stop or a convenient rest station for travelers headed south to the Big Bend. Fort Stockton might be again thought of as it once was: the Garden Spot of West Texas, an Oasis in the Desert" (Freedman 1990). As a result of returned springflows, the City of Fort Stockton hired the U.S. Geological Survey to better understand the relationship between groundwater levels and flow from Comanche Springs (Small and Ozuna 1993).

Since pumping began in earnest in the Leon-Belding Irrigation Area in the late 1940s, it peaked in the 1960s and 1970s (Harden and others 2011, Clark and others 2013[15]) before gradually decreasing to pre-1955 to 1955 levels by the 1980s. Since 1985, pumping has remained at

[15] Harden and other (2011) show irrigation peaking in 1971 while Clark and others (2013) show it peaking in 1960 (Table 9.1). Based on Harden and other's (2011) composite hydrograph (Figure 5.10), pumping peaked in 1965 with a secondary peak in 1975 (we did not review the data and procedures for this figure).

about that level, allowing flows to occasionally return to Comanche Springs during the winter months.

It is unclear how often and long the springs have flowed after they seasonally reappeared in 1986. Norris and Opdyke (Appendix A) noted that Texas A&M AgriLife Extension Service in Fort Stockton measured flow at the springs in early 1992 with the highest measured flow at 14 cubic feet per second. Norris and Opdyke (Appendix A) reported on measurements at the springs between 2008 and 2010 with peak flows just under 8.5 cubic feet per second. Siegmun (2011) wrote about the springs and posted photos of them flowing in February 2011. The USGS (2020a) measured flows between 3.24 and 5.07 cubic feet per second from January 19 to March 4, 2011. The springs are reported to have flowed for a period of a few months each winter since that time (Ty Edwards, personal communication). We first observed the flows in person in March 2018 and several times in 2018–2019 and 2019–2020. Over the past ten years, the springs generally return late in the year (Christmas in 2019) and flow into spring (and were flowing as of May 6, 2020).

Springflows over the last decade were significant enough to prompt emergency structural repairs to the pool's foundation in 2018. Engineers from WJE found significant erosion under the pool due to springflow and flow dynamics around the concrete structure on which the swimming pool rests.

The majority of the flow occurs from Big Chief Spring; however, limited flow also occurs from up-stream springs at higher elevations. Norris and Opdyke (Appendix A) found that about 89.6 percent of the flow on February 9, 2009, came from Big Chief and Government springs while 3.2 percent came from Blue Hole, 1.0 percent from Koehler's Spring, and 5.1 percent from unnamed springs (Headwater, Jail, and Church springs were not flowing at the time). Similar to Norris and Opdyke's observations for winter flows, we found, besides Big Chief Spring, Blue Hole and Koehler's springs flowing as well as unnamed seeps along the canal. We also found seeps in the canal as far south as Spring Street with no flow from Headwater, Jail, and Church springs.

Working with the Middle Pecos Groundwater Conservation District and using the rating curve generated by Norris and Opdyke (Appendix A), we estimated total springflow on a near-weekly basis during the winter and spring of 2019-2020 and observed that the springs started to flow on Christmas Day in 2019, rapidly rose in volume to about 10 cubic feet per second, and held steady at that level until about the end of February when they dwindled to nothing by the end of April (Appendix C).

In response to the recent, consistent return of the springs, the Pecos County Water Control and Improvement District No. 1—which still exists in the area as a rural water supplier—has had to start maintaining the main ditches again, at least from the springs to just to the north of Interstate-10. The gates at the diversion dam have long rusted away, so the Improvement District has, at different times, moved dirt to by-pass the shallow concrete dam to allow flow to move down Comanche Creek, or, alternatively, replaced the dirt to direct water down the main irrigation canal.

This past year, the Improvement District has removed brush from the two main diversion points, one just south of Interstate-10 where the main canal bi-furcates into the Highline Ditch, which heads north, and into the 7-D Ditch, which heads east. In both cases, the quality of the ditches rapidly deteriorates north of Interstate-10, with the Highline ditch sanded in and unusable by the time it reaches Stone Road, about 5,000 canal-feet north of Interstate-10. As of 2020, the Improvement District had blocked water flow through the Highline Ditch by dumping dirt into the canal just north of the Interstate-10 access road.

The 7-D ditch emerges just on the north side of the Interstate-10 access road and enters a siphon that goes underneath the bed of Comanche Creek before emerging on the other side about 250-feet away. The siphon has been compromised, so the water bubbles up into Comanche Creek into a small, shallow pond that sometimes laps over the frontage road, which sits in the bed of the creek. Enough water flowed down the creek during the 2019–2020 winter season that the Improvement District had to enforce its water rights to prevent a landowner from capturing and selling the water (Gonzales, 2020).

At present, with the recent work by the Improvement District, the old canal system is set up to collect and then divert flow into Comanche Creek. If flows are brought back year-round, the Improvement District will likely improve the canals north of the interstate to put the water to beneficial use.

7.0 Groundwater Management

Although the Texas Supreme Court established the Rule of Capture in Texas in 1904, the Texas Legislature, empowered by the Water Conservation District Amendment to the state constitution in 1917, allowed for the creation of locally controlled groundwater conservation districts in 1949 (Mace 2016). Groundwater conservation districts can generally regulate groundwater production from aquifers. A groundwater district was first discussed in July 1951 with the Texas Board of Water Engineers (Fort Stockton Pioneer 1951h). After receiving a petition from G.P. Crone and 59 other people (Fort Stockton Pioneer 1959c), the State Board of Water Engineers designated Subdivision No. 1 of the Pecos Underground Water Reservoir in 1959 which, at the time, was required to create a groundwater conservation district (TNRCC 1997).

An unnamed citizens' group represented by attorney Paul Dionne—who owned a Fort Stockton law firm with Hart Johnson, the attorney for the Pecos County Water Control and Improvement District No. 1's lawsuit again the groundwater irrigators—approached Fort Stockton's city council in July 1962 about forming a groundwater conservation district and solving the city's water issues during the city's consideration of purchasing groundwater from Buchanan Farms near Belding (Fort Stockton Pioneer 1962a). The citizens' group expressed concerns on the non-sustainable use of groundwater in the area as demonstrated by annual decreases in water levels and noted that a groundwater conservation district was a tool to balance supply and demand (Fort Stockton Pioneer 1962a). They also presented a proposal to the city council; however, Mayor Jones Taylor wasn't receptive, asking "Would anybody care to read this proposal? I'm not going to read it" (Fort Stockton Pioneer 1962a).

Among other items, the group proposed that the city (1) create a groundwater conservation district, (2) manage the aquifer sustainably, (3) join forces with the county to purchase or condemn land irrigated with groundwater to retire groundwater pumping, (4) use Leon Lake as a supply reservoir for the city, and (5) sell excess water (Fort Stockton Pioneer 1962a). In the fall of 1962, the law firm of Johnson and Dionne circulated petitions to form a groundwater conservation district for the Fort Stockton, Leon-Belding, and Hovey areas of Pecos and Brewster counties (Fort Stockton Pioneer 1962b). We were not able to determine if Johnson and Dionne succeeded in getting 50 landowner signatures and submitting it to the state, but we do know that a groundwater conservation district was not formed at that time. Fort Stockton's city council considered but tabled further study toward forming a groundwater conservation district in 1970 (Fort Stockton Pioneer 1970).

Perhaps inspired by the return of the springs in 1986, there was a push at that time to create a groundwater conservation district in Pecos County, something Clayton Williams, Jr., the son of Clayton Williams, spent thousands of dollars to oppose (Freedman 1990, Somma 1994). Ultimately, the city council tabled the creation of a groundwater conservation district (Shropshire 1990).

The Texas Legislature created the Middle Pecos Groundwater Conservation District, among others, in 1999 as part of Senate Bill 1911. The act put a moratorium on the adoption of long-term management, including local confirmation of the district, taxing, and the development of a groundwater management plan, until after September 1, 2001. Unusually, the act also called for the subsequent legislature, meeting in 2001, to ratify the creation of the district(s) before they could be created. The subsequent legislature ratified the creation of the Middle Pecos Groundwater Conservation District with House Bill 1258. Voters confirmed the district in 2002 (Williams 2010).

The boundaries of the district are the same as Pecos County which includes the Leon-Belding Area and Comanche Springs. Except for some minor modifications in its enabling legislation, the district has the general powers of a Chapter 36 district. In its latest groundwater management plan (Weatherby 2015), the district describes its mission as helping to "…maintain a sustainable, adequate, reliable, cost effective and high quality source of groundwater to promote the vitality, economy and environment of the District."

The groundwater district granted historic and existing use permits based on use in the 15 years before the district's creation (Mulder 2015). Historic and existing use permits were tied to their use at the time they were granted (Mulder 2015).

The groundwater district has established three groundwater management zones, Management Zone 1 for the Leon-Belding Irrigation Area, Management Zone 2 for the Bakersfield Irrigation Area, and Management Zone 3 for the Coyanosa Irrigation Area (Figure 7.1). Management Zone 1 includes the traditionally recognized Leon-Belding Irrigation Area but also Comanche Springs and a broad area in-between as well as an area that extends towards the northwest, including parts of Upper Coyanosa Draw (Figure 7.2). The limits of these groundwater management zones are defined by model cells from the groundwater availability model for the Edwards-Trinity (Plateau) Aquifer (MPGCD 2018). Within these management zones, the groundwater district established benchmarks for sustainable groundwater in their rules (Williams 2010).

The groundwater district's rules (MPGCD 2018) include aquifer-based production limits based on achieving the desired future conditions of aquifers in the district. Desired future conditions are what districts, working collectively inside a groundwater management area, want their aquifer to look like during the regional and state water planning horizon, generally 50 years in the future (Mace and others 2008). The Texas Water Development Board then uses these conditions to estimate the modeled available groundwater, a volume of water that can be pumped to achieve the desired future condition (Mace and others 2008). Groundwater districts are then required by law to include the desired future condition statement and modeled

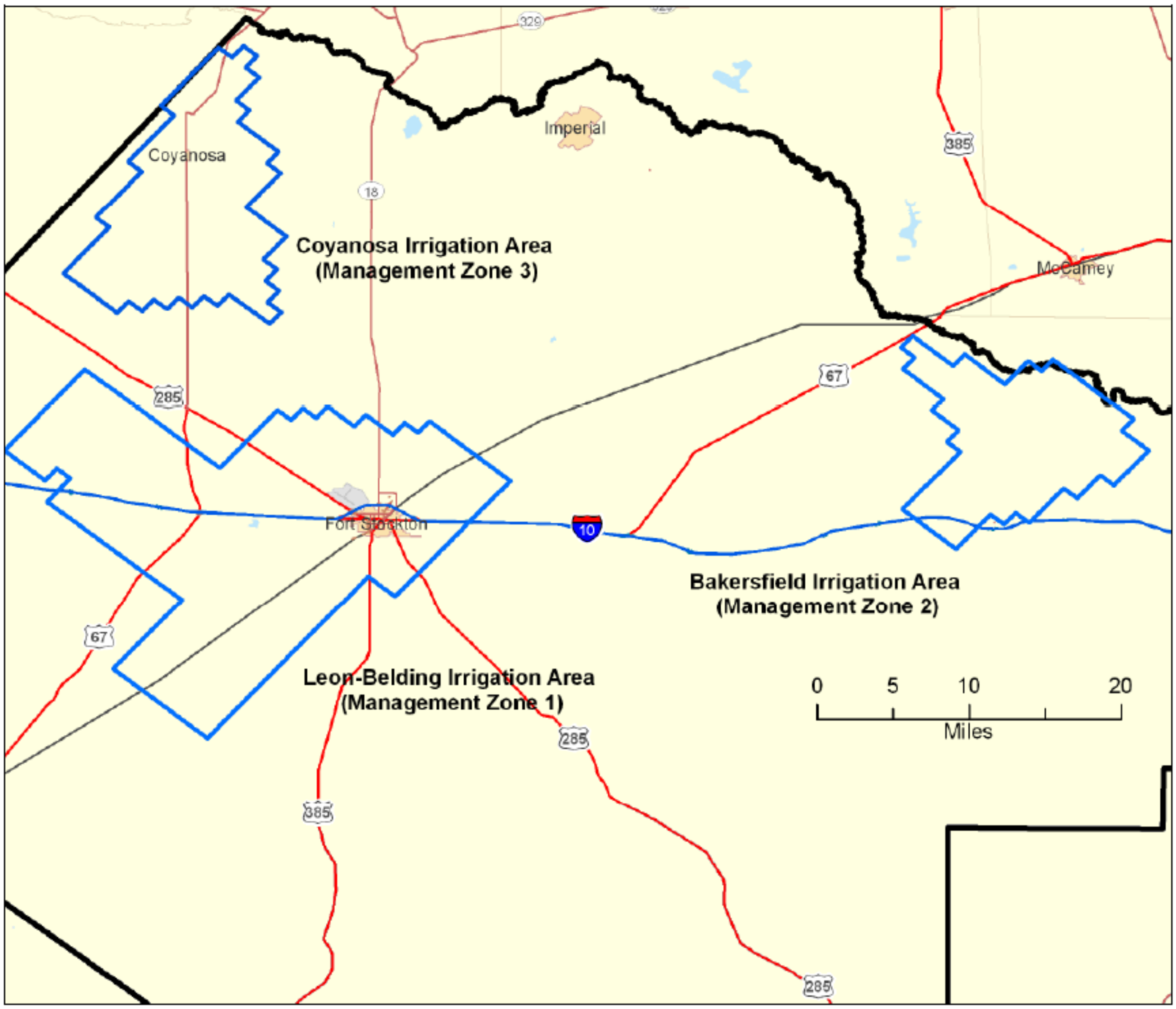

Figure 7.1: Groundwater management zones in the Middle Pecos Groundwater Conservation District (from Williams 2010).

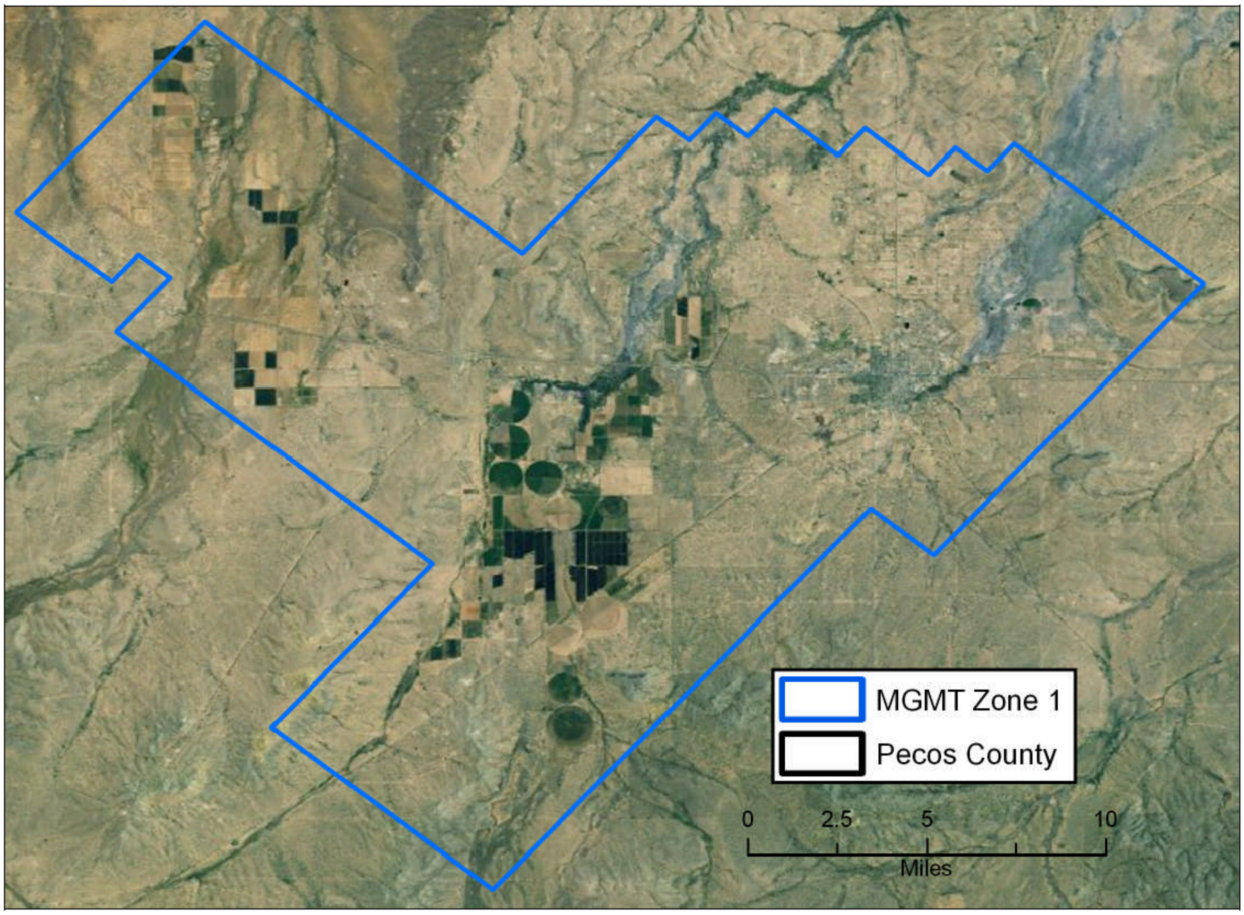

Figure 7.2: Management Zone 1 (from Williams 2010).

available groundwater number in their groundwater management plans and then pass and enforce rules to achieve the desired future condition (Mace and others 2008). Districts that do not perform these tasks may be subject to enforcement by the Texas Commission on Environmental Quality, including dissolution of the district (Mace and others 2008). Regional water planning groups are then required to use modeled available groundwater numbers for their planning activities, planning activities that ultimately roll into the state water plan (Mace and others 2008).

The Middle Pecos Groundwater Conservation District is located in groundwater management areas 3 and 7. Groundwater Management Area 3 includes the northern part of Pecos County, defined by the extent of the Pecos Valley Aquifer but underlain by the Edwards-Trinity Aquifer among several minor aquifers. The rest of the county and district is in Groundwater Management Area 7, which includes the Edwards-Trinity Aquifer among several minor aquifers. Groundwater Management Area 3 includes two groundwater conservation districts, and Groundwater Management Area 7 includes 21 groundwater conservation districts. Because our study area is in Groundwater Management Area 7, we will focus our discussion there.

The desired future conditions for the Edwards-Trinity Aquifer in Groundwater Management Area 7 is 14 feet of drawdown in 2070 compared with water levels in 2010 (Hutchison 2018a, Table 7.1). The modeled available groundwater for the Edwards-Trinity Aquifer in Groundwater Management Area 7 is about 117,000 acre-feet per year compared with about 120,000 acre-feet of permitted usage and an average of about 65,000 acre-feet per year of production (Jones 2018, Table 7.2, Figure 7.3). Note that these values are for the entirety of the Edwards-Trinity Aquifer in the district in Groundwater Management Area 7 and not solely for the Leon-Belding Irrigation Area (although the Leon-Belding Irrigation Area comprises most of the production in this area).

Desired future conditions for the Capitan Reef Complex, Dockum, and Rustler aquifers in the GMA 7 portion of the groundwater district are 4 feet of drawdown in 2070 compared with 2007, 52 feet of drawdown compared with 2012, and 69 feet of drawdown compared with 2009, respectively (Hutchison 2018b, 2018c, 2018d; Jones 2018; Table 7.2). Permitted use and production in the Rustler Aquifer is about equal to the modeled available groundwater while permitted use and production in the Capitan Reef Complex Aquifer is well under the modeled available groundwater (figures 7.4 and 7.5, respectively).

The Middle Pecos Groundwater Conservation District plans to use proportional reductions (known in the Texas groundwater subculture as "The Haircut Method") to achieve the desired future conditions (Rule 10.3[b], MPGCD 2018). For example, if permitted pumping needs to be reduced 10 percent to meet the desired future conditions, then all the relevant permits would be reduced by 10 percent. The primary driver for a proportional reduction is not meeting the desired future condition, which could occur through over-permitting (in conjunction with the resulting overpumping), overpumping (perhaps informed by an overestimate of the modeled available groundwater), or a decrease in recharge or inflows.

The district also has the ability to modify permits to achieve its desired future condition (Rule 10.3[c], MPGCD 2018). The district notes that it will issue permits, to the extent possible, "up to the point that the total volume of exempt and permitted groundwater *production* will achieve an applicable Desired Future Condition for each such aquifer or its subdivision in the District." (emphasis added, Rule 10.3[d], MPGCD 2018). The use of the word "production" means that the permitted use of groundwater could exceed the modeled available groundwater volume for an aquifer in its subdivision (that is, the management zone).

The proportional adjustment of permits has, effectively, three tiers: (1) historic and existing use permits, (2) production permits, and (3) exempt use (Rule 10.3[d], 10.4; MPGCD 2018). Historic and existing use permits are those that, at the time the district was created, were pumping or had been pumping in the previous 15 years. Production permits are those that were issued after the historic and existing use period. Exempt uses are, in general, for domestic and livestock use and for a well used solely to provide supply water for an oil and gas rig (Rule 11.3; MPGCD 2018).

Table 7.1: Average drawdowns for the desired future conditions in Management Zone 1 (from MPGCD 2018).

Year	Average drawdown
2015	3
2020	7
2025	10
2030	13
2035	17
2040	20
2045	23
2050	26
2055	29
2060	32

Table 7.2: Desired future conditions, modeled available groundwater volumes, and recent production for the relevant aquifers in the Groundwater Management Area 7 Portion of the Middle Pecos Groundwater Conservation District (ac-ft = acre=feet, PV = Pecos Valley).

Aquifer	Desired Future Conditions (DFC) expressed in drawdown	Modeled Available Groundwater	Authorized Permitted Production	2018 Production* (ac-ft)	2017 Production* (ac-ft)	2016 Production* (ac-ft)	2015 Production* (ac-ft)	2014 Production* (ac-ft)	Estimated Exempt Production
Edwards Trinity/PV	14 feet compared to aquifer levels on 2010	117,309	120,205	60,073	58,369	64,513	75,096	65,145	3,542
Capitan Reef	Total net drawdown not to exceed 4 feet in MPGCD in 2070 compared to 2006 aquifer levels	26,164	3,397	1,586	1,281	1,043	1,351	1,249	50
Dockum	52 feet compared to aquifer levels in 2012	2,022	-	-	-	-	-	-	-
Rustler	69 feet compared to aquifer levels in 2009	7,040	7,291	6,754	7,013	5,909	4,796	5,833	50

* Includes exempt and non-exempt production. Production values provided by MPGCD, 2019.

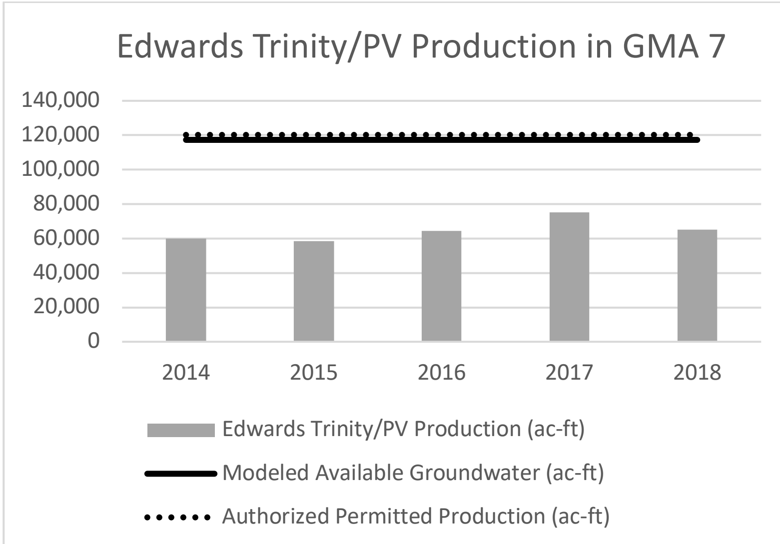

Figure 7.3: Modeled available groundwater, permitted production, and recent production for the Edwards-Trinity Aquifer in Groundwater Management Area 7 (data from the Middle Pecos Groundwater Conservation District; ac-ft = acre-feet, GMA = groundwater management area, PV = Pecos Valley).

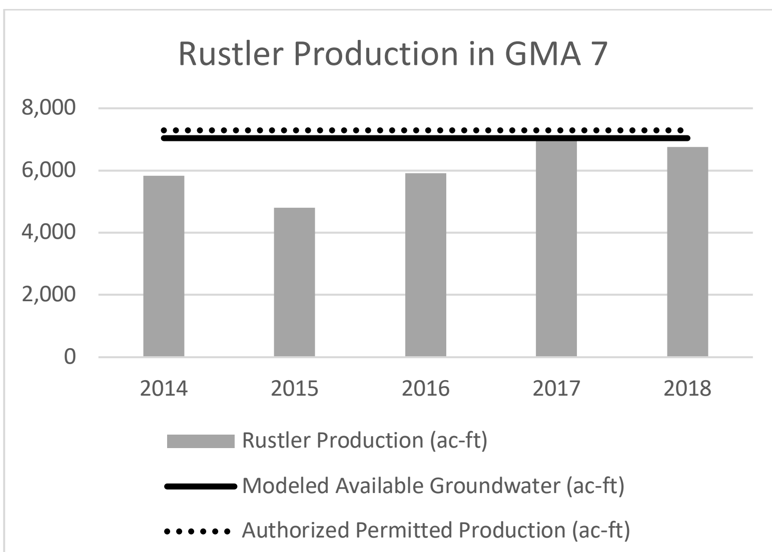

Figure 7.4: Modeled available groundwater, permitted production, and recent production and for the Rustler Aquifer (data from the Middle Pecos Groundwater Conservation District; ac-ft = acre-feet, GMA = groundwater management area).

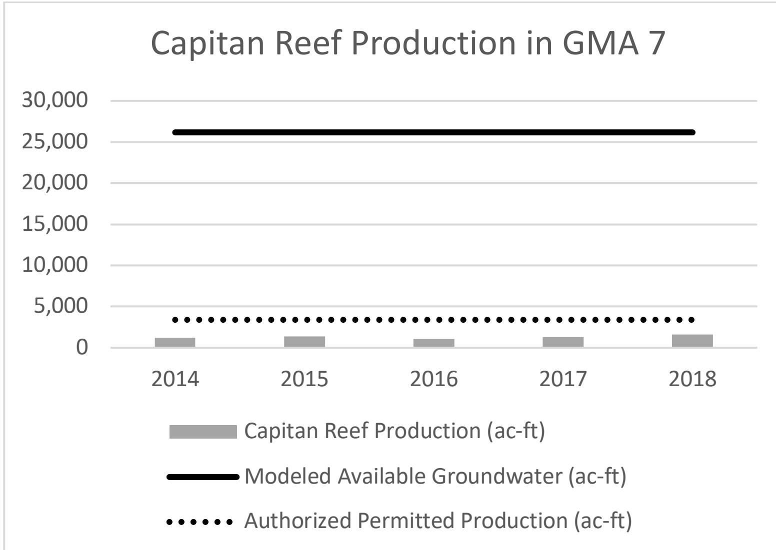

Figure 7.5: Modeled available groundwater, permitted production, and recent production and for the Capitan Reef Aquifer (data from the Middle Pecos Groundwater Conservation District; ac-ft = acre-feet, GMA = groundwater management area).

Once production exceeds the modeled available groundwater, production permits are proportionally reduced first (Rule 10.3[d], MPGCD 2018). Once those permits are exhausted, historic and existing use permits are then proportionally reduced (Rule 10.3[d], 10.4; MPGCD 2018). Because exempt use (generally household and livestock wells) is exempt from the production rules of the district, they remain untouched.

The district has established benchmarks of "sustainable groundwater use" over time to "avoid impairment" of the desired future condition as defined by the groundwater availability model. Average drawdowns from the groundwater availability model for Management Zone 1 consistent with the desired future conditions steadily increase over time, from 7 feet in 2020 to 32 feet in 2060 (Table 7.1).

The groundwater district doesn't define sustainability in its groundwater management plan or rules. In the groundwater field, sustainability generally[16] means the "…development and use of ground water in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences" (Alley and others 1999). This definition appropriately has a strong policy component, namely "unacceptable environmental, economic, or social consequences."

In the case of the Edwards-Trinity Aquifer in Pecos County, the Middle Pecos Groundwater Conservation District—under the umbrella of desired future conditions defined by groundwater conservation districts in the groundwater management areas—is deciding what is

[16] There is no definitive hydrogeological definition of sustainability, but there is agreement that sustainable pumping is pumping that can occur indefinitely.

unacceptable. The district appears to be focused on managing the aquifer such that is can be used indefinitely to the benefit of historic and existing use permittees and exempt users. However, the desired future condition allows for a systematic decrease in water levels through 2060 in Management Zone 1, suggesting that the desired future conditions are not sustainable.

The groundwater availability model (Anaya and Jones 2009 with modifications by Hutchison and others 2011) used to develop and evaluate the desired future condition is probably not a good tool for assessing sustainability and impacts—and thus modeled available groundwater—for this part of the aquifer. The model is super-regional and doesn't reflect critical details of the local hydrogeology.

8.0 Groundwater Export?

In the late 1990s, as drought took hold in the American Southwest, drought also grabbed onto West Texas, lowering reservoir levels and prompting the larger cities in West Texas, primarily Midland and Odessa but also San Angelo and Abilene as well as the Colorado River Municipal Water District, to look for new water. Given that it wasn't raining enough to fill reservoirs, groundwater became a preferred choice.

Water from the Leon-Belding Irrigation Area is enticing to West Texas municipalities. Unlike more local groundwater choices from the Ogallala and Pecos Valley aquifers, water from the Leon-Belding Irrigation Area can be sustainable, a rarity in dusty and dry West Texas. However, distance, water quality, and permit uncertainty remain as challenges. The Leon-Belding Irrigation Area is about 95 miles from Midland and Odessa, thus requiring a substantial pipeline to transport the water. With total dissolved solids at about 1,400 milligrams per liter, a receiving city would probably have to desalinate the water, something Fort Stockton does with its water from the Leon-Belding Irrigation Area. Permit uncertainty comes from how the Middle Pecos Groundwater Conservation District responds to the export (more on this later) as well as other local pumpers, including other farmers and Fort Stockton, concerned about their supply. Despite these challenges, income from potential water sales remains an alluring prospect in contrast to the income generated by agricultural irrigation. In short, it is difficult to make a living farming in the Leon-Belding Irrigation Area; Clayton Williams Jr. noted that the family farm only made a profit in 3 of the previous 11 years as of 2015 (Mulder 2015a).

Seeing an opportunity to sell groundwater, the Williams family—under the umbrella of the family company, Fort Stockton Holdings—filed for a permit from the groundwater district in July 2009 to export groundwater from Leon-Belding Irrigation Area to Midland-Odessa (Mulder 2015a, Paul 2016a). The groundwater district subsequently rejected the permit application (Mulder 2015a, Paul 2015b). In response, Fort Stockton Holdings filed a lawsuit (Mulder 2015a). In September 2015, the district court ruled in favor of the groundwater district (Mulder 2015b). Midland considered the water, but ultimately went another direction (Mulder 2015).

After leasing the water from Fort Stockton Holdings (Paul 2016a), Republic Water of Texas LLC also applied for an export permit with plans to build a $225 million pipeline to Odessa (Mulder 2015a) in February 2016 (Paul 2016a). In support of Republic's project and permit, Odessa had signed a letter of interest in late 2015 (Paul 2015b) to buy 16 million gallons of water per day at $3.50 per thousand gallons (Paul 2016a). After the groundwater district tabled the permit, Republic filed lawsuits in district and federal courts in 2016 against the groundwater district for refusing to grant export permits to Fort Stockton Holdings' water rights, joining Fort Stockton Holdings' ongoing lawsuit (Paul 2016a). The federal lawsuit alleged a taking of private property rights by the groundwater district (Paul 2016a). The total export project was estimated at $200 million and would serve several municipal and industrial users (Paul 2016c).

Odessa drilled a $817,000 test well in the Capitan Reef Aquifer in the area and then approached Fort Stockton about exporting water, but the City of Fort Stockton balked at the terms (Paul 2015a). The district was also considering granting a permit to STW Water Resources out of Midland to export water from the Capitan Reef Aquifer to municipalities and others (Paul 2015b). The Colorado River Municipal Water Authority, a regional water supplier to Midland and Odessa, also expressed interested in Williams' water, resulting in a lawsuit threat from Republic Water (Paul 2016c).

As hydraulic fracturing created a new oil and gas boom in the Permian Basin, oil and gas companies also became interested in the water supplies of the Leon-Belding Irrigation Area. In March 2015, the groundwater district granted a permit to Pecos SS to pump 3.2 billion gallons a year (about 10,000 acre-feet per year) from the Edwards-Trinity Aquifer about 25 miles east-northeast of Fort Stockton to oilfields 50 miles away in Crane County (Paul 2015a). Pecos SS was hoping to sell the water at 50 cents a barrel (Paul 2015a), which amounts to about $3,900 an acre-foot. Fort Stockton Holdings contested the Pecos SS permit (Paul 2015b).

Given that the groundwater district had been considering Fort Stockton Holdings' permit request for almost five years, the Williams Family lobbied the legislature on the permit and export issue, resulting in a House Natural Resource Committee hearing in Fort Stockton in 2016 (Elliott 2019). The committee chair, Lyle Larson, subsequently filed a bill in March of 2017 that would put the groundwater district under review (Elliott 2019) of the Texas Sunset Act (Larson 2017).

In April 2017, the groundwater district approved a settlement by a vote of 8 to 1 that included (CBS7 2017a):

- The groundwater district granting Fort Stockton Holdings a new operating permit for production and use of groundwater from the Edwards-Trinity Aquifer for municipal, industrial, and agricultural purposes inside and outside of the district.
- Fort Stockton Holdings filing a request to reduce its historical and existing use permits from 47,418 acre-feet to 28,400 acre-feet.
- Fort Stockton Holdings agreeing not to file a permit application to produce additional quantities of groundwater from the Edwards-Trinity Aquifer for five years and, if

more water is needed, to explore using deeper aquifers such as the Capitan Reef Aquifer.

- Republic Water of Texas LLC withdrawing its own application and paying the groundwater district its court costs and fees of $404,990.54.
- Republic Water of Texas LLC agreeing not to file a permit in the future to produce from the Edwards-Trinity Aquifer on properties in Fort Stockton Holdings' application.
- The groundwater district including a permit condition for Fort Stockton Holdings that restricts production based on aquifer-level triggers.
- Fort Stockton Holdings agreeing to meter and report water produced from wells for agricultural use and water transported for municipal and industrial purposes off of the property.
- Fort Stockton Holdings agreeing to pay the groundwater district an export fee of $0.025 per 1,000 gallons.
- Fort Stockton Holdings agreeing to request State Representative Lyle Larson to remove the groundwater district from his sunset bill and to not support any legislative efforts referencing the groundwater district that could impact or change the current regulatory structure, governance, management and or/funding mechanism of the district.

In July 2017, the groundwater district issued an export permit to Fort Stockton Holdings (CBS7 2017b).

In 2018, the Cockrell Interests LLC, who owns and operates a pecan farm in the Leon-Belding Irrigation Area, sued the groundwater district over the settlement due to concerns on the long-term sustainability of the aquifer in response to Fort Stockton Holdings' proposed export, which would increase pumping (Elliott 2019). At the time we prepared this report, Cockrell Interests LLC, Fort Stockton Holdings, and the groundwater district were still in discussions over the lawsuit.

By 2019, the Williams Family was considering selling their water to the oil and gas industry (Elliott 2019) since the Permian Basin was booming with fracking wells. In 2017, the City of Fort Stockton signed an agreement to sell up to 390,000 barrels of water a day (about 18,300 acre-feet a year) for 10 cents a barrel (about $800 an acre-foot) to a company supplying the oil and gas industry (Elliott 2019).

9.0 Bringing Back Year-Round Springflow: How Much Pumping for How Much Flow?

To bring back year-round flow, there are two key questions: (1) How much flow is needed from the springs? and (2) How much do we need to reduce pumping from the Edwards-Trinity Aquifer to achieve that flow?

9.1 How Much Springflow Is Needed?

To address how much springflow is needed, we focused on the amount of flow required to protect health and human safety if the county returned the spring back to its natural state (or at least its state as of the 1938 construction of the current bathhouse) for swimming. To make this estimate, we hired a contractor to survey the elevation of the natural pool bottom to assess the topography and volume of the natural spring-basin floor (Turner 2019, Appendix D). Using photography and Vectorworks, Turner (2019) estimated a natural basin volume of between 1.0 million and 1.5 million gallons. Turner (2019) notes that this range is "a starting point for refinement." A more detailed assessment, including a plan to restore the natural pool, should be done in the future if year-round flows are achieved.

There are no public health standards for natural pools and bodies of water (beyond those established by U.S. Environmental Protection Agency for general water quality for public contact). Public pools are required to have a turnover rate of six hours (Texas Administrative Code, Title 25, Rule §265.187[b][1][A]), which suggests a flow of 2,800 to 4,200 gallons per minute (6.2 to 9.3 cubic feet per second) would be needed. Based on this information, we assumed that a minimum flow of 10 cubic feet per second would be required to reopen the pool.

A reinvigorated Comanche Springs could be used as a refugia for endangered species in the area, including the Comanche Springs pupfish located at San Solomon Springs, a species originally described at Comanche Springs. In 2004, Pecos County approached Texas Parks and Wildlife Department about restoring the natural site and reintroducing the Comanche Springs pupfish and the Pecos gambusia. The discussions resulted in plans to build a ciénega on Comanche Creek behind the Catholic Church inspired by the gruta that the church used for baptisms when the springs still flowed. The plan was to use a well as a source of water and to recirculate flow.

Returned springflows also offers the opportunity for the re-introduction of the previously extirpated species. The U.S. Fish and Wildlife Department offers voluntary Safe Harbor Agreements for landowners whose actions contribute to the recovery of endangered and threatened species (USFWS 2005). These agreements provide assurances from the U.S. Fish and Wildlife Service that if landowners adhere to the agreements, the Department won't require additional actions without the landowners' consent. At the end of the agreement period, the property can be returned to its formal state without repercussions. A Safe Harbor Agreement could be used to assure locals that the full force of the Endangered Species Act would not be activated with the return of springflow and the reintroduction of endangered species while at the same time providing critical refugia for these species.

The unpublished plan by Texas Parks and Wildlife Department and local governmental bodies envisioned a ciénega that would benefit a number of birds (Pied-bill grebe, Green-winged teal, Northern shoveler, Sora, Virginia rail, Belted kingfisher, Black phoebe, Marsh wren, Swamp sparrow, Common yellowthroat, Red-winged blackbird, Yellow-headed blackbird), other fish (Mexican tetra, Green sunfish, Channel catfish, Headwater catfish), reptiles (Blotched watersnake, Texas spiny softshell turtle), and plants (Sand spikerush, Common cattail, Giant sacaton, Olney bulrush, Fourwing saltbrush, Gooding willow, Rio Grande cottonwood, Common reed, Common buttonbush). In 2009, Fort Stockton Holdings developed a plan to rework the old spring run from Koehler's and Blue Hole to just past the current pool into a more natural setting with artificial year-round flow.

We did not conduct a scientific study on how much springflow would be needed for the reintroduction of species at Comanche Springs; however, experience with other habitats in the area suggest 10 cubic feet per second would be enough to achieve sufficient flows for this purpose. For example, flow at Diamond Y Springs, which supports the Leon Springs pupfish and other endangered and threatened species, was about 3 to 5 cubic feet per second in 1987 (Veni 1991). Phantom Lake Springs near Balmorhea, which also hosts related endangered species, flowed at 10 cubic feet per second in the 1930s before ceasing flow in May 2001; this spring currently has a low-flow pump providing minimal flows to maintain the species (Ridgeway and others 2004).

9.2 How Much Does Pumping Need to Be Reduced?

To know how much pumping would need to be reduced to achieve a year-round flow at Comanche Springs of at least 10 cubic feet per second would ideally involve having accurate measurements of pumping amounts and springflows when the springs went dry in the 1950s. While we fortunately have good measurements of springflows during that time, we unfortunately do not have good direct measurements of pumping during that time. Therefore, we can try to estimate the amount of pumping required to achieve 10 cubic feet per second through indirect methods, such as historical spring behavior and numerical groundwater flow modeling.

In all approaches, a water budget—where the water is coming from and going—is key. When a groundwater system is in equilibrium, inflows equal outflows. Inflows may include recharge, flow into the area through the aquifer, cross-formational flow, and, in some cases, irrigation return flows. Outflows may include springflows, baseflows to rivers, cross-formational flow, flow out of the area through the aquifer, and well production. When inflows are greater that outflows, water levels, and perhaps natural discharge, rise, and when outflows are greater than inflows, water levels, and perhaps discharge levels, decline.

9.2.1 Using the Water Budget

The aquifer was presumably in equilibrium before people drilled wells in the area. We do not have direct measurements of recharge to the Edwards-Trinity Aquifer or of the volume of water upwelling from the underlying Rustler Aquifer, which geochemical evidence shows a clear connection to the Edwards-Trinity Aquifer in the Leon-Belding Irrigation Area (Bumgarner and others 2012). We do have two predevelopment (before there were any high-volume wells in the area) measurements of flow at Comanche Springs—one measured in the summer of 1899[17] and the other measured in July 1904—that average 65 cubic feet per second (about 47,000 acre-feet per year if those flows are assumed to be indicative of the entire year; Atkins 1927; note that Brune [1975, 1981] incorrectly reported these values as water-year averages). Subsequent measurements of flow from Comanche Springs at a different equilibrium (after the Leon Springs Irrigation Company drilled flow-enhancing wells next to Leon Springs) suggests stable springflows from year to year (Figure 5.8 between 1941 and 1947), consistent with a regional source of much older cross-formational flow.

The only pre-development mention of flow at Leon Springs we found was 10,000,000 gallons per day (about 15.5 cubic feet per second or 11,000 acre-feet per year) by the Fort Stockton Pioneer (1911a). Another newspaper account suggests that the flow at Leon Springs was about 16.5 cubic feet per second (12,000 acre-feet; see Footnote 3), and this was probably after water-levels were dropped 10.5 feet at the springs. Other springs in the area suggest there could be higher overall springflows, but it's not clear if those springs are connected to the same flow system through the Edwards-Trinity Aquifer, through the Rustler Aquifer, or fed, for example, by stream losses in Comanche Creek that subsequently reappear downstream (although temperature, water quality, geology, and timing of cessation of flow suggest there is not a direct connection). Therefore, we assumed that Comanche and Leon springs constitute the majority, if not all, of spring discharge in the area.

Because we have different measurements at different times when the system was in equilibrium, we can calculate the water budgets under several different scenarios and compare them. Adding the pre-development reported values for Comanche and Leon springs results in a total flow of 80.5 cubic feet per second (58,000 acre-feet per year). Annual average flow at Comanche Springs (44.5 cubic feet per second in USGS 2020a) and Leon Springs after the Leon Springs Irrigation Company drilled its flow-enhancing wells at Leon Springs (23 cubic feet per second in 1920 via Brune 1975) add up to about 67.5 cubic feet per second (49,000 acre-feet per year) for water year 1920.

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[17] "Summer" is how this measurement is dated in Taylor and Hoyt (1905). Note that USGS (2020a) shows a date of 1/1/1899, probably as a default since a date wasn't specified with the measurement.

Armstrong and McMillion (1961) provide a number for 1958 where they calculated the combined discharge from wells and springs in the Fort Stockton-Leon-Belding area to be about 70 cubic feet per second (51,000 acre-feet). We calculated springflow deficits by subtracting measured springflow at Comanche Springs from that measured in 1920 (and proportionally adjusted flow from Leon Springs to go dry in 1958) and found the deficit to be 47,900 acre-feet per year in 1958 (Table 9.1; see Appendix E for a detailed description of this approach). For a more recent estimate, pumping amounts in the Leon-Belding Irrigation Area have been about 46,000 acre-feet per year between 2012 and 2016. With Comanche Springs flowing about 10 cubic feet per second for about four months (about 2,500 acre-feet per year), the recent outflow water budget adds up to about 67 cubic feet per second (48,500 acre-feet per year).

Harden and other (2011) came up with a combined pre-development flow of 90 cubic feet per second (65,000 acre-feet per year) for the two springs, a number used to inform recharge in their groundwater model; however, by using springflow data from different years (1899 for Comanche Springs and 1920 for Leon Springs with flow-enhancing wells), they double-counted the flow Leon Springs captured from Comanche Springs after the completion of the flow-enhancing wells drilled in 1915 and 1916.

As previously mentioned, accounting for the increased flow at Leon Springs still results in about 10 cubic feet per second of unaccounted flow from Comanche Springs. One hypothesis is that these early measurements are in error. Sharp and others (2003) stated that springflow measurements taken before 1920 in the area were "less reliable" but do not provide a justification for that statement. The measurement was made by T.U. Taylor of the Civil Engineering Department of The University of Texas at Austin using either a Price or pygmy meter (Taylor and Hoyt 1905) and a field procedure similar to today's procedure using that equipment (Fahlquist 2020). Taylor and Hoyt (1905) describe the gaging location as "Comanche Creek near Fort Stockton" and in the writeup refers to the creek rather than the springs, suggesting the possibility he measured flow farther downstream where he may have been capturing other springflows. Unfortunately, an investigation of the paper files and notes for these measurements was not possible due to the SARS-CoV-2 pandemic.

An alternate hypothesis is that the numbers are accurate, but we are not accounting for additional discharge from the system that occurred between 1904 and 1920. For example, an artesian flowing well (with an unreported flow) was drilled to supplement flow at San Pedro Springs in 1916–1917 (Fort Stockton Pioneer 1922); however, we don't believe that San Pedro Springs or the other downstream springs were connected to the primary flow system from the Leon-Belding Irrigation Area to Comanche Springs. Other artesian and near-surface wells were drilled downstream from Leon Springs, but the yields were not high and, similar to the downstream wells of Comanche Springs, don't appear to have a direct connection to the primary flow system. Given that San Pedro Springs went dry before Comanche Springs despite being at a lower elevation lends support to the hypothesis that they were fed by Comanche Springs flows that recharged alluvium in Comanche Creek and then re-emerged at San Pedro

Table 9.1: Estimates of pumping in the Leon-Belding Irrigation Area and Management Zone 1.

Year	Spring flow	This study	Audsley (1956)	Armstrong & McMillion (1961)	TBWE (1981)	District	Clark & others (2014)	Harden & others (2011)
1942	x	3,000					14,000	
1943	x	3,100					16,000	
1944	x	3,200					18,000	
1945	x	3,300					19,000	6,500
1946	x	3,000					24,000	10,000
1947	x	5,800					30,000	13,000
1948	x	9,400					28,000	19,000
1949	x	9,600					29,000	22,000
1950	x	13,500					30,000	27,000
1951	x	22,400					26,000	31,000
1952	x	22,700					27,000	34,000
1953	x	26,900					28,000	45,000
1954	x	21,900					27,000	56,000
1955	x	33,100	20,600				29,000	74,000
1956	x	43,400	36,000				29,000	78,000
1957	x	46,300					55,000	91,000
1958	x	47,900		49,000			71,000	104,000
1959	x	47,200					87,000	115,000
1960	x	47,200					79,000	124,000
1961	x	>49,000					70,000	125,000
1962	-	>49,000					70,000	128,000
1971	-	>49,000					38,000	142,000
1975	-	>49,000					38,000	111,000
1979	-	>49,000			<90,147		24,000	93,000
1986	x	<49,000					27,000	72,000
1987	x	<49,000					24,000	69,000
1991	x	46,300					23,000	67,000
2008	?					43,000	34,000	78,000
2009	x	47,100				49,000	47,000	68,000
2010	x	47,300				48,000	47,000	72,000
2011	x	48,000				59,000		
2012	x	>49,000				52,000		
2013	x	>49,000				48,000		
2014	x	>49,000				52,000		
2015	x	<49,000				43,000		
2016	x	<49,000				46,000		
2017	x	<49,000						
2018	x	<49,000						
2019	x	46,000						
2020	x	<49,000						

For our estimates (under "This study"), we used springflows by the U.S. Geological Survey (1942 through 1962); reports of no springflow for 1971, 1975, and 1979; reports of flows (but no reported measurements) for 1986 and 1987; measured springflow by Texas A&M AgriLife Extension Service for 1992 (as reported by Norris and Opdyke [Appendix A]); measured springflow by Norris and Opdyke (Appendix A); measurements by U,S. Geological Survey for 2011 through 2014; and our observations and measurements for 2018 through 2020. The estimate for 1956 by Audsley (1956) is from proportionally adjusted his 1955 estimate by the increased number of authorized acres for 1956 that he noted.

as well as other downstream springs. On the other hand, the Pecos County Water Control and Improvement District No. 1 and individual farmers were drilling wells in the district's service area to replace declining spring flows and may have affected San Pedro and the other springs. More study is needed here.

We believe that the near agreement of the four water budgets—one from 1920, two from 1958, and one from 2012–2016—suggests 49,000 acre-feet per year is the more accurate estimate of the system's water budget. But given the uncertainty, we considered the number to be between 49,000 to 58,000 acre-feet per year. The near agreement of the four water budgets—three with very different production amounts—suggests we can use a simple water-budget model to represent inflows and outflows, namely that less water for pumping means proportionally more water for springflow. Accordingly, we could subtract 10 cubic feet per second (7,200 acre-feet per year) from 49,000 to 58,000 acre-feet per year and use that as the pumping target; however, that 10 cubic feet per second is a cumulative average for the year. In reality, current groundwater use is seasonal, with most of the pumping occurring during the growing season. This results in higher water levels in the winter months—which is why we are seeing springflows today during the winter—and lower water levels in the summer months—which is why the springs dry up every spring.

The hydrograph for springflow in the early 1950s (Figure 5.8) suggests that maintaining a daily minimum of 10 cubic feet per second might require an annual average springflow of 20 cubic feet per second (note the about 30 cubic feet per second seasonal swing in 1951, 1952, and 1954 when springflow reached spot-minimums of about 8 cubic feet per second).[18]

If pumping is reduced to bring back flow at Comanche Springs, Leon Springs should return as well. During the increase of pumping in the 1950s, Leon Springs went dry for good in 1958 whereas Comanche Springs dried up for several decades starting in 1961. For the 1948 water year, Leon Springs and its flow-enhancing wells discharged about 15 cubic feet per second (Brune 1975), which is about 11,000 acre-feet per year. Using a water budget approach of U.S. Geological Survey data for Comanche Springs, and proportionally adjusting flow at Leon Springs according to flow declines at Comanche Springs suggests that Leon Springs flowed about 8,600 acre-feet per year in 1951, 1952, and 1954 when daily flows at Comanche Springs bottomed out at about 8 cubic feet per second. This is slightly overestimated since Leon Springs went completely dry for the full year in 1958 as opposed to 1961 for Comanche Springs.

[18] Norris and Opdyke (Appendix A) noted a 7 cubic feet per second variation in seasonal springflow between 1921 and 1926 and that this variation could be due to fluctuations in precipitation, evaporation, atmospheric temperature, and other weather conditions but also the withdrawal of groundwater. While it's certainly possible that when the Leon Springs Irrigation Company sank its flow-enhancing wells around Leon Springs, they only opened them during the irrigation, it's far more likely that they left them flowing year-round, something that was common in the early days of flowing artesian wells (Mace 2016). Furthermore, the Irrigation Company built Leon Lake to capture winter flows to maximize water use during the irrigation season suggesting that the flow-enhancing wells were left flowing year-round. If the wells were left flowing year-round, the 7 cubic feet per second variation may be indicative of the recharge component to the Edwards-Trinity Aquifer in the Leon-Belding Irrigation Area.

Maintaining a cumulative yearly average of 20 cubic feet per second (14,500 acre-feet per year) and accounting for induced flow at Leon Springs would allow about 26,000 to 35,000 acre-feet per year of pumping (with the lower number more likely).

This simple screening analysis does not account for potential increased cross-formational flow from the Rustler Aquifer due to lowered water levels in the Edwards-Trinity Aquifer from pumping nor the capture of flows out of the irrigation area through the Edwards-Trinity Aquifer. However, the near agreement of the pre- and post-pumping water budgets post 1919 suggests that changes to these potential flows have little to no influence on the overall water budget for the Leon-Belding Irrigation Area.

9.2.2 Using the Groundwater Model

Several numerical groundwater flow models have been developed for the Edward-Trinity Aquifer, including regional models by Kuniansky and Ardis (2004) and Anaya and Jones (2009), the latter later updated by Hutchison and others (2011). Because of the local and unique nature of groundwater in the Leon-Belding Irrigation Area, these regional models are not the appropriate tools for local management of the system (see, for example, the comparison of Anaya and Jones' [2009] regional model to the local model developed by Harden and others [2011]). As a consequence, Thornhill and others (2008) developed a local model for Clayton Williams Farm, Inc. Thornhill and others (2008) assumed no cross-formational flow, something we now know to be the major contributor of flow to the Edwards-Trinity Aquifer in the Leon-Belding Irrigation Area. DBSA (2010) developed a model for Fort Stockton to evaluate the impact of pumping on the city's wells in the Leon-Belding Irrigation Area.

Harden and others (2011) expanded the geographic scope of the Thornhill model and included cross-formational flow from lower formations, naming the new model the Western Pecos County Groundwater Model. The model includes the western part of Pecos County, most of Reeves County, and parts of Brewster, Crane, Crockett, Culberson, Jeff Davis, Loving, and Upton counties. The Western Pecos County Groundwater Model assumes no irrigation return flows based on soil studies; however, subsequent water-quality testing indicates some irrigation return flows due to detections of pesticides as well as elevated nutrients (Bumgarner and others 2012). The Western Pecos County Groundwater Model assumes that (1) the highest measured flow at Comanche Springs (48,000 acre-feet per year) plus flow at Leon Springs in 1920 (16,600 acre-feet per year, but rounded up to 17,000) was the pre-development flow (total of 65,000 acre-feet per year) and (2) all of that flow from the springs came from recharge to the Edward-Trinity Aquifer. As previously discussed, 49,000 to 58,000 acre-feet per year is a more reasonable and supported number, and isotopic studies indicate that most flow into the system sources from cross-formational flow instead of local recharge.

The model does a fairly good job of matching water levels and, for the most part, matching springflow declines in Leon Springs (the model underestimates flow duration) and Comanche Springs (the model overestimates flow duration). However, models with unknown water fluxes (such as recharge and cross-formational flow) unconstrained by water fluxes can be nonunique, meaning a variety of aquifer parameters, inflows, and pumping can result in similar results, especially in karst systems.

Harden and others (2011) calibrated their model to higher levels of pumping in Management Zone 1 than Clark and others (2014) (compare Figure 9.1 to Figure 9.2). Pumping in the model by Harden and others (2011) has three phases of increased pumping from (1) essentially no pumping in 1944 to about 35,000 acre-feet per year in 1952, to (2) about 125,000 acre-feet per year in 1960, to (3) a peak of about 140,000 acre-feet per year in 1971 (Figure 9.1). After that, pumping declines to about 70,000 acre-feet per year in 1985 and remains between about 70,000 to 80,000 acre-feet per year through 2010 (Figure 9.1).

Pumping in the model by Clark and others (2014) also has three phases of increased pumping from (1) about 12,000 acre-feet per year in 1940 to about 27,000 acre-feet per year in 1947, to (2) about 27,000 acre-feet per year through 1956, to (3) a peak of about 80,000 acre-feet per year in 1959 (Figure 9.2). After that, pumping declines to about 20,000 acre-feet per year in 1980 and remains at about that level through 2006 after which it increases to about 40,000 acre-feet per year for 2007 through 2010 (Figure 9.2). Oddly, the model by Clark and others (2014) has most of the pumping in the Trinity and not the Edwards.

Groundwater pumping in the groundwater model by Harden and others (2011) is substantially higher than other estimates. For example, in 1955, Harden and others (2011) had 74,000 acre-feet per year in the model for Management Zone 1 while Audsley (1956) estimated 20,600, Clark and others (2014) had 29,000, and we calculated 32,800 using the spring discharge deficit approach (see Appendix E for a description of this approach). In 1958, Harden and others (2011) had 104,000 acre-feet per year while Armstrong and McMillion (1961) estimated 49,000, Clark and others (2014) had 71,000, and we calculated 47,700. In 1971, Harden and others (2011) had 142,000 acre-feet per year while Clark and others (2014) had 38,000, and we calculated more than 49,000. In 1979, Harden and other (2011) had 93,000 acre-feet per year Management Zone 1 while TBWE (1981) had 90,147 for the entirety of Pecos County. In 2010, Harden and others (2011) had 72,000 acre-feet per year while the groundwater district had 48,000 from meters, Clark and others (2014) had 47,000, and we calculated 47,300.

The end result of this analysis is that it appears that, after 1953, pumping in the model developed by Harden and others (2011) is overestimated by 50 percent, so we need to be careful when interpreting model results when evaluating pumping in relation to flows at the springs.

With its current calibration, the model shows that if current levels of pumping (circa 2011) are maintained, water levels in the Leon-Belding Area will remain at about their current elevation (Harden and others 2011, their Figure 5.6). If permits are fully pumped, water levels can be expected to decline—without reaching equilibrium—through 2060, resulting in about 35 feet of baseline water-level decline (Harden and others 2011, their Figure 5.6).

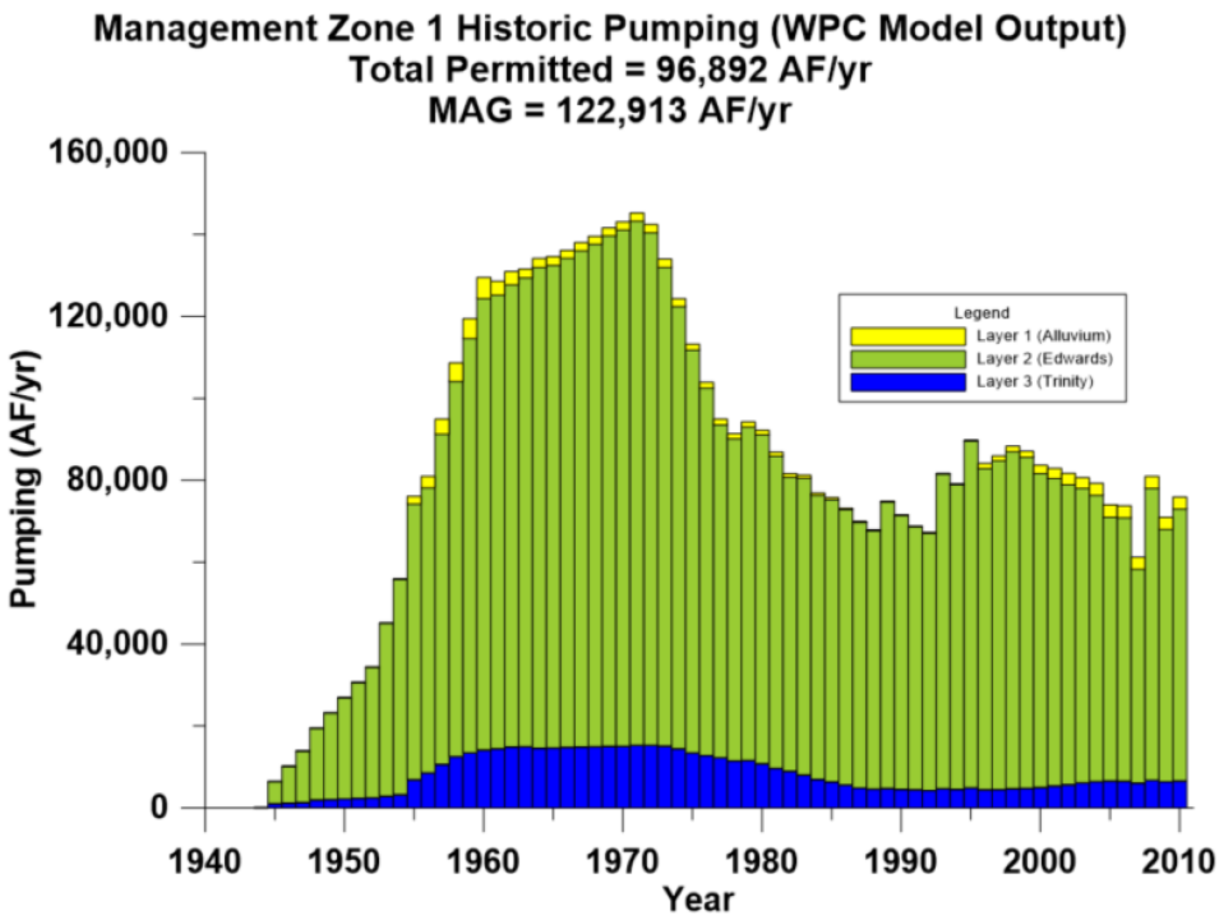

Figure 9.1: Pumping used in the calibrated model by Harden and others (2011) for Management Zone 1 (from Hutchison 2017b).

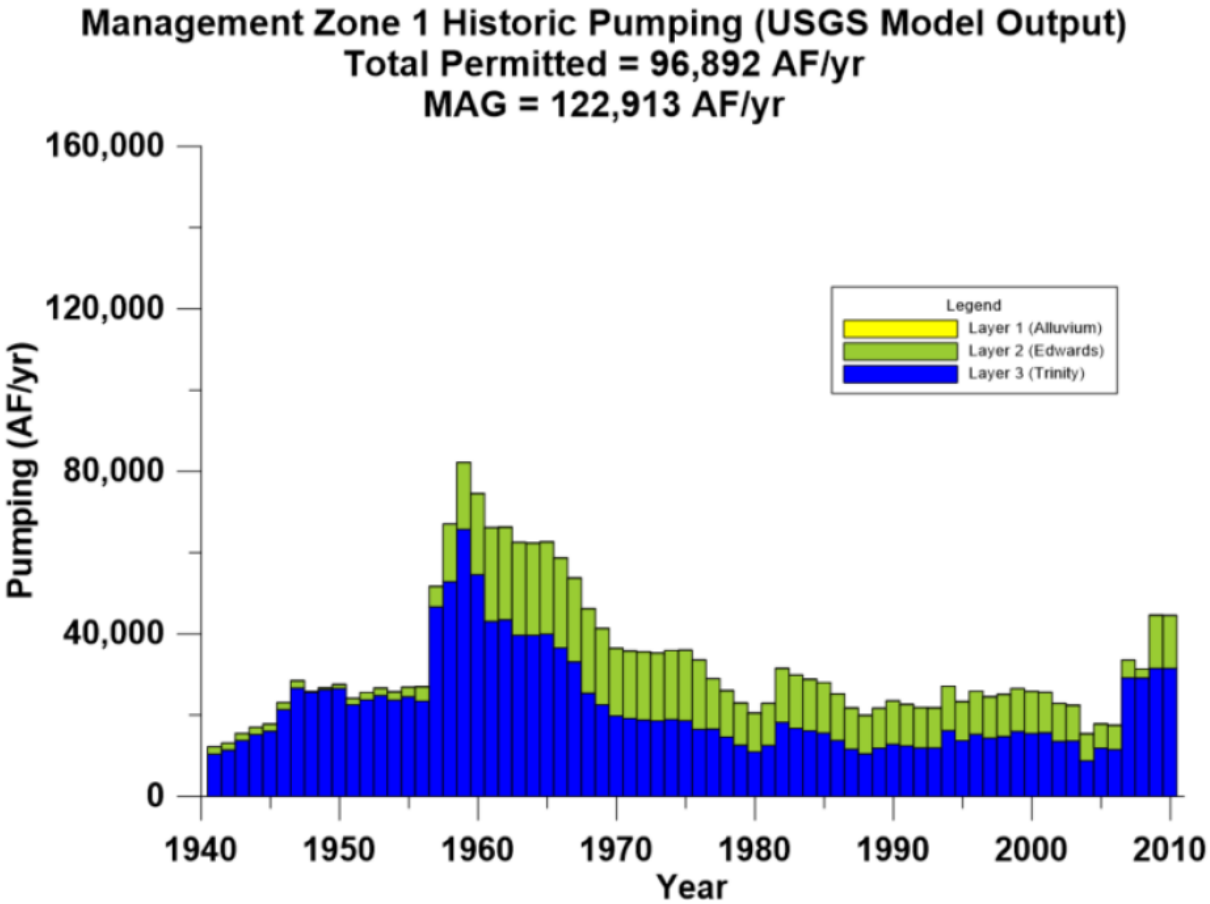

Figure 9.2: Pumping used in the calibrated model by Clark and others (2014) for Management Zone 1 (from Hutchison 2017b).

Clark and others (2014) developed a model of the greater area in cooperation with the Middle Pecos Groundwater Conservation District, Pecos County, City of Fort Stockton, Brewster County, and Pecos County Water Control and Improvement District No. 1. This model used six-month stress periods to simulate the irrigation and non-irrigation seasons. Based on low precipitation and high evapotranspiration, Clark and others (2014) assumed that recharge was low to non-existent over much of the model area except where they assumed 2 inches per year in a five-mile wide area along the mountain front of the Glass Mountains. They also assumed 0.2 inches per year of recharge due to irrigation return flows as indicated by the detection of nutrients and pesticides in the aquifer (Clark and others 2014).

Hutchison (2017a), working for the groundwater conservation districts in Groundwater Management Area 7, found the model by Clark and others (2014) to not be suitable for predictive simulations. Hutchison (2017b) subsequently reviewed the model by Harden and others (2011) and found it to be a better tool for evaluating the impacts of pumping in Management Zone 1. Hutchison (2017b) ran the Harden and others (2011) model for different pumping scenarios (Figure 9.3) as a sensitivity analysis to see what those pumping scenarios might mean for flows at Comanche Springs (Figure 9.4). Because the model uses annual stress periods—in other words, it averages pumping and springflows over the year—we also need to consider interannual variations like we did in the previous section, meaning we probably need an annual average flow of 20 cubic feet per second to achieve a minimum of 10 cubic feet per second at the springs during the summer. That results in about 40,000 acre-feet per year of pumping (using figures 9.3 and 9.4). Assuming that this is overestimated by 50 percent, we would need actual pumping to be about 27,000 acre-feet per year to maintain the target year-round springflow.[19]

This number (27,000 acre-feet per year) is close to what we found using the water-budget approach (26,000 acre-feet per year). Given the uncertainty with the pre-development flow of Comanche Springs, maintaining a yearly average flow of 20 cubic feet per second (14,500 acre-feet per year) at Comanche Springs would allow about 26,000 to 35,000 acre-feet per year of pumping (with the lower end of that range more likely).

[19] We acknowledge that the relationship between pumping and springflow may not be linear in the model; however, without an adequately configured and parameterized model, this is the best we can do to account for overestimated pumping and inflow in the model. Since we're employing several lines of evidence to support our estimate, we're using this approach to ensure that we our numbers are somewhat consistent.

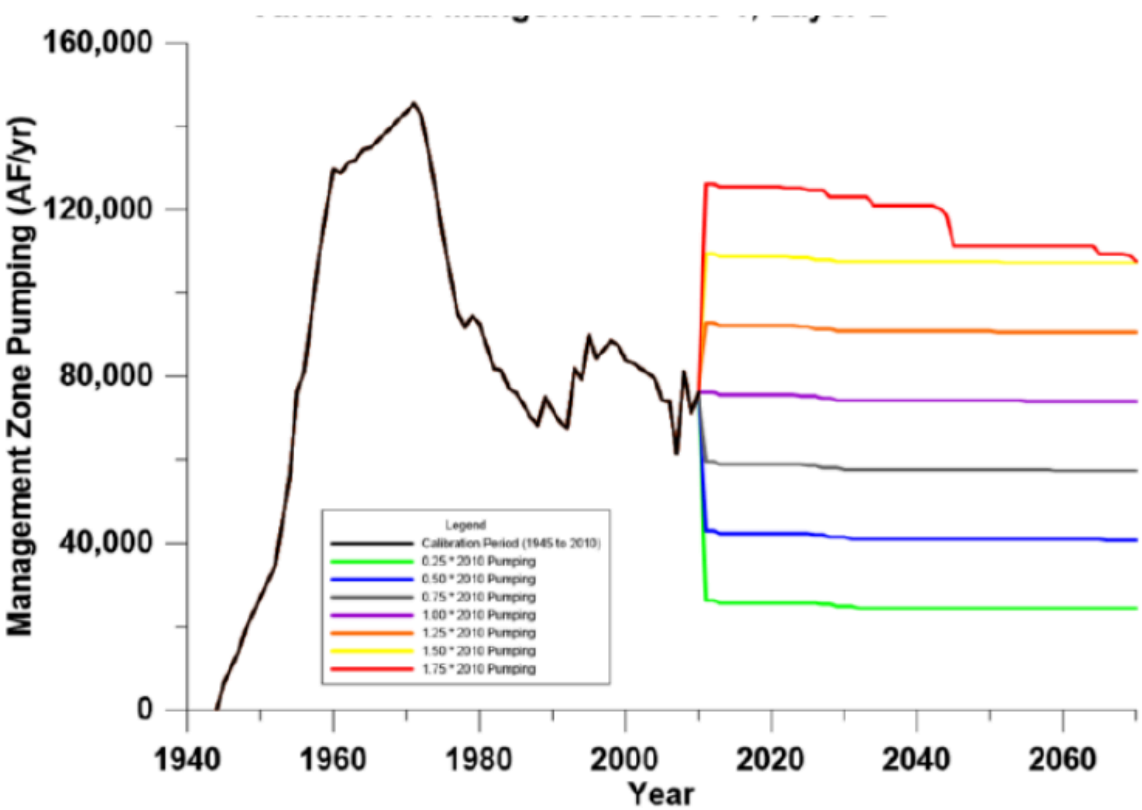

Figure 9.3: Historical pumping in the Harden and others (2011) model for Management Zone 1 (black line) and seven scenarios of projected pumping (colored lines; from Hutchison 2017b).

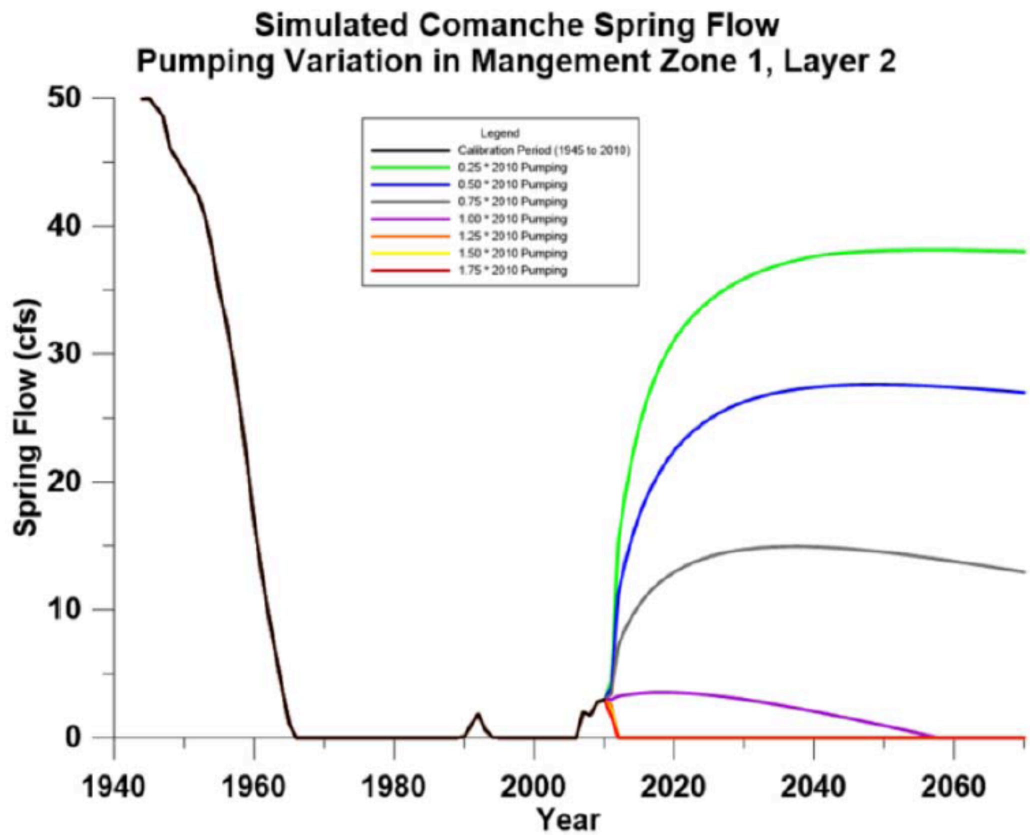

Figure 9.4: Simulated flow at Comanche Springs for the historical pumping in the Harden and others (2011) model for Management Zone 1 (black line) and for seven scenarios of projected pumping (colored lines; from Hutchison 2017b; see Figure 9.1 for the pumping scenarios).

10.0 Economics

We identified and evaluated potential options to reduce pumping in the Edwards-Trinity Aquifer to increase flow to Comanche Springs. The analysis included a preliminary range of unit costs and an estimation of potentially available water volumes that could be achieved through each alternative reviewed.

10.1 Management Zone 1 Groundwater Permits

Comanche Springs contributing zone is located within Management Zone 1 of the Middle Pecos Groundwater Conservation District. Spring flow is reduced due to groundwater pumping from the Edwards-Trinity Aquifer within the management zone, primarily for agricultural irrigation of hay (alfalfa), grains, cotton, and pecan trees. In addition, about 10 percent of the total pumping in the Edwards-Trinity Aquifer within the management zone is for municipal uses, including the drinking water supplies of the City of Fort Stockton, the Pecos County Water Control and Improvement District #1, and a Texas Department of Criminal Justice facility. Groundwater pumping in the Leon-Belding Irrigation Area is believed to have the largest impact of spring flow (Figure 10.1). More distant groundwater pumping within the management zone is thought to be less connected to flow in Comanche Springs.

Much of the permitted pumping from the Edwards-Trinity Aquifer is used for irrigation. Approximately 74,000 acre-feet per year from the Edwards-Trinity Aquifer is permitted to agricultural producers. Of this total, reported water use has averaged 46,272 acre-feet per year from 2008 through 2016 indicating that a large portion of the permitted volume is unused (Figure 10.2). According to the groundwater district, agricultural water use varies with the price of alfalfa. During drought and higher alfalfa prices, groundwater pumping increases as agricultural producers grow more hay. However, groundwater pumping has been well below the permitted volume since 2008, which includes years with relatively high hay prices.

A large portion of the agricultural land was planted with field crops including hay and grains with about 3,600 acres planted with pecan trees (figures 10.3 and 10.4). More than 2,200 acres appeared to be fallow at the time the aerial image was taken. The land may have been idled or between crops. However, some fields appear to have not been irrigated for many years based upon available aerial imagery.

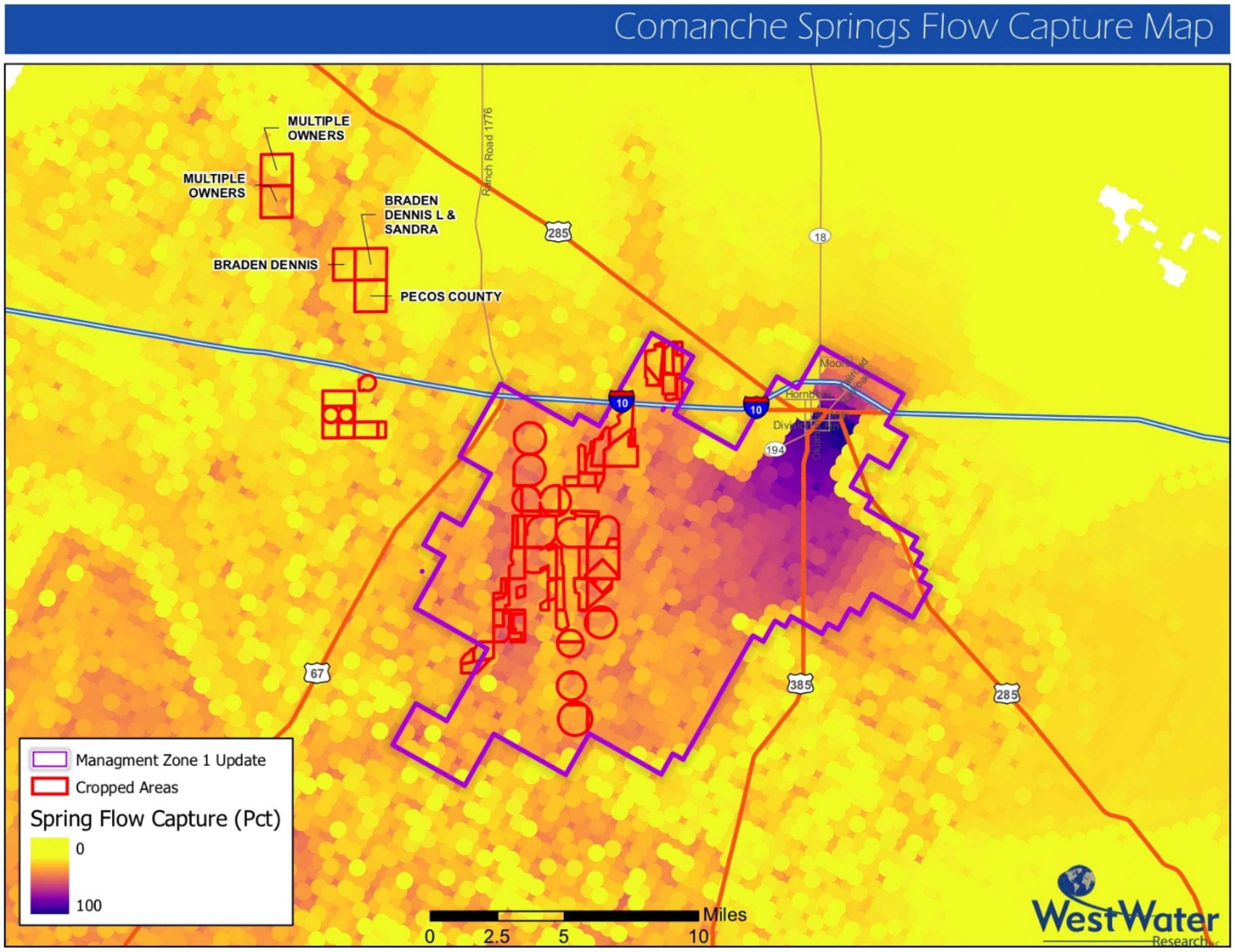

Figure 10.1: Modeled contributions of groundwater storage to springflow at Comanche Springs. Darker colors represent areas where groundwater production would be more likely to reduce springflow. The largest volumes of groundwater production are in the Leon-Belding Irrigation Area at the far western edge of a proposed New Management Zone 1 (outlined in purple), where cropped areas are outlined in red (data from Middle Pecos Groundwater Conservation District).

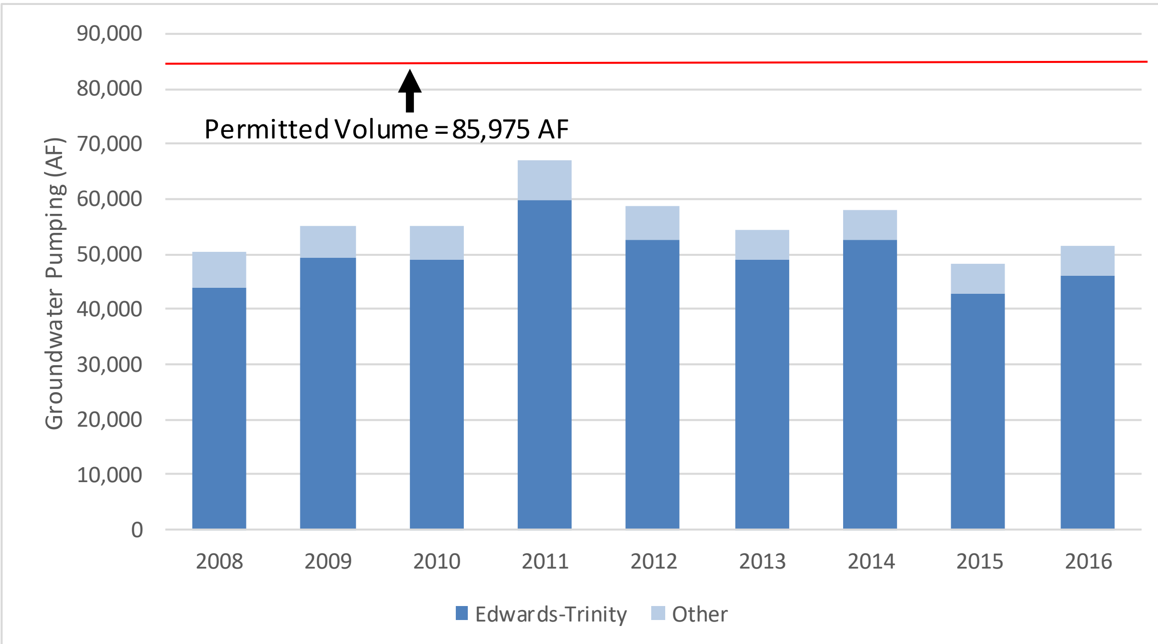

Figure 10.2. Permitted volume and annual groundwater use in Management Zone 1 from 2008 through 2016 (data from the Middle Pecos Groundwater Conservation District).

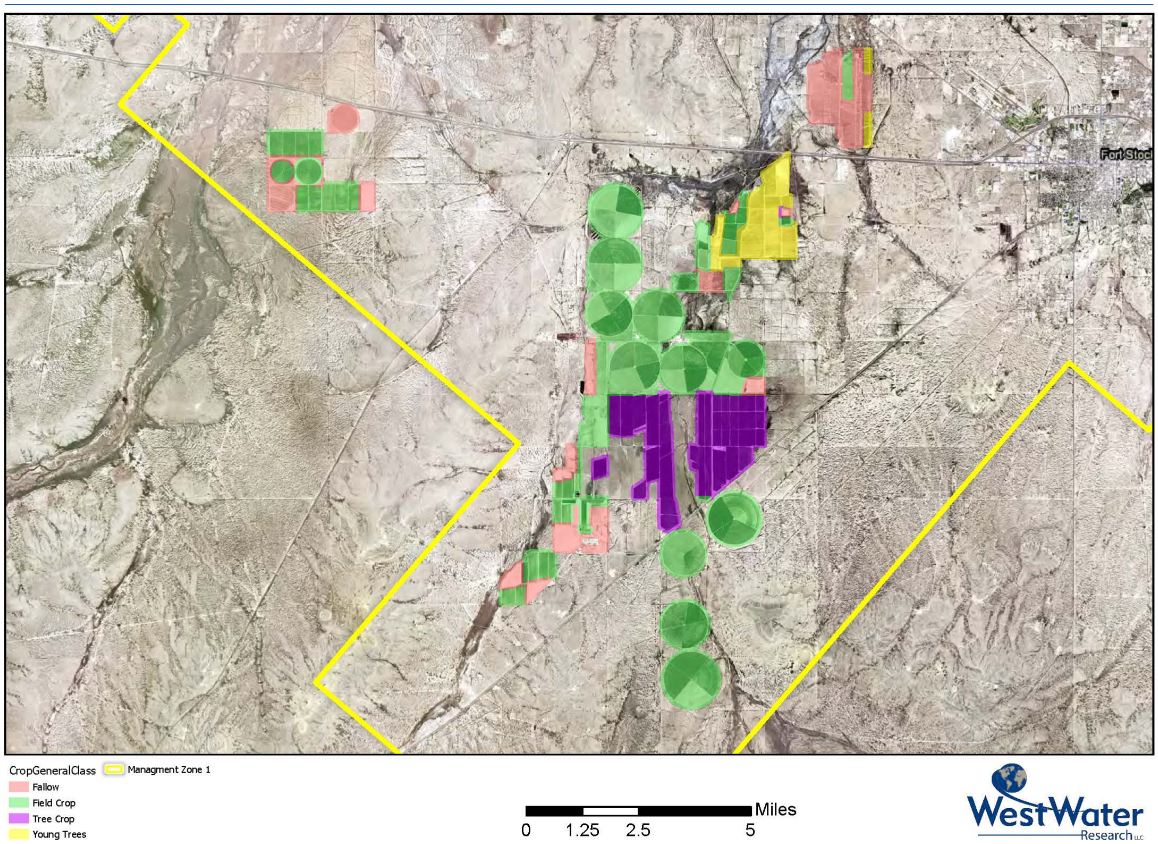

Figure 10.3: Irrigated land and general crop categories produced during 2016.

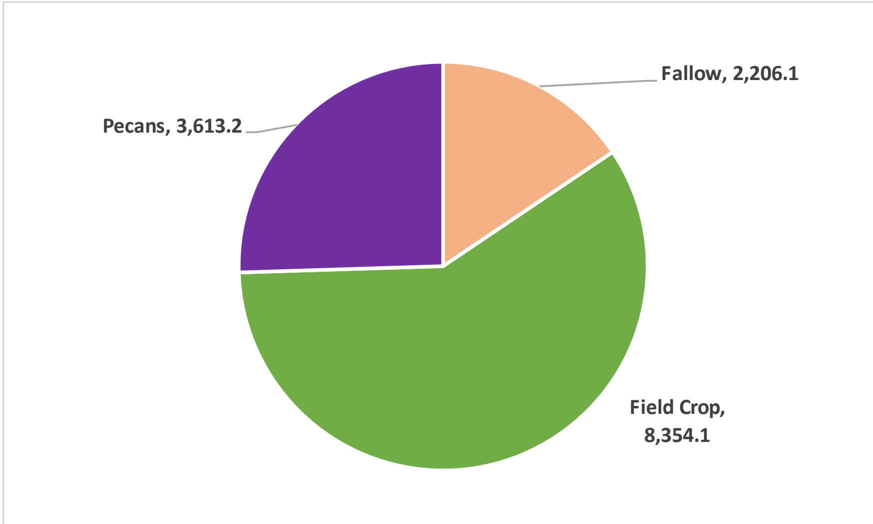

Figure 10.4: Summary of the crops grown within the Management Zone 1 during 2016.

Groundwater permit ownership within the management zone is relatively concentrated (Table 10.1). About 65 percent of the total permitted volume from the Edwards-Trinity Aquifer is leased or owned by one corporate owner (Groundwater Owner 1; Table 10.1). The second largest permitted amount is held by the City of Fort Stockton, with approximately 12 percent of the permitted volume. Two pecan producers, Groundwater Owner 2 and Groundwater Owner 3, each own approximately 10 percent of the permitted volume. The Texas Department of Criminal Justice (State of Texas) owns approximately 4 percent. We used Pecos County land ownership data to identify the agricultural land associated with each owner. Note that the available county landownership data is incomplete so the crop acres should only be considered approximate. In addition, owner names associated with parcels may not match the names on the groundwater permits, which further complicates matching permit/pumping data with land ownership.

While agricultural groundwater use dominates, the groundwater district has also issued a groundwater export permit to Groundwater Owner 1 that would allow Edwards-Trinity Aquifer groundwater to be pumped and conveyed for use outside of the district for non-agricultural purposes. The export permit allows for up to 28,400 acre-feet to be pumped and exported annually or used within the district for municipal, industrial, and/or agricultural purposes. To export the water, Groundwater Owner 1 agreed to retire 28,400 acre-feet of historic and existing permits in exchange for a new operating permit which would be subject to curtailment ahead of historic and existing permits in the event that groundwater district needed to limit groundwater pumping to meet desired future conditions. Even after the retirement, Groundwater Owner 1 will own or hold long-term leases on rights for nearly 19,000 acre-feet of historic and existing permits to the Edwards-Trinity Aquifer.

Table 10.1: Summary of the largest permitholders in the Edwards-Trinity Aquifer.

Owner	Permitted volume (acre-feet per year)	Fallow (acres)	Field (acres)	Trees (acres)	Total (acres)
Groundwater Owner 1	48,550	151	5,649	189	5,990
City of Fort Stockton	9,078	0	3	130	133
Groundwater Owner 2	7,771	78	155	1,794	2,027
Groundwater Owner 3	7,400	0	121	703	825
Texas Department of Criminal Justice	3,200	207	573	0	781
Groundwater Owner 5	1,820	7	273	0	280

Groundwater Owner 1 and one of its partners have solicited interest from water-short communities in the Permian Basin. The City of Odessa signed a letter of intent to receive the groundwater at a delivered price of $3.50 per thousand gallons, or $1,140 per acre-foot (Paul 2015). The price that Groundwater Owner 1 would have received if that contract had moved forward is unknown. In May 2020, it was announced that Groundwater Owner 1 had secured an agreement with three cities in West Texas for the entirety of its production permit. The agreement, structured as a take or pay contract, escalates the price per unit of water over time but begins at a unit amount of $0.30625 per 1,000 gallons, equivalent to $99.79 per acre-foot (this deal was announced when our report was nearly completed; we describe the details of this deal in Section 11).

10.2 Initial Groundwater Volume Target

Annual agricultural groundwater pumping from the Edwards-Trinity Aquifer in Groundwater Management Zone 1 averaged approximately 46,000 acre-feet per year from 2012 through 2016. Our analysis began with initial groundwater modeling which indicated that a 25 percent reduction in pumping from reported pumping in 2010 would result in approximately 10 cubic feet per second on an annual basis at Comanche Springs. Based upon detailed photogrammetry of the primary Comanche Springs complex at the municipal bathhouse, that level of flow would be sufficient to promote recreational contact with unchlorinated spring water. However, the modeled pumping in 2010 is higher than reported by the groundwater conservation district using more recent information. As a result, the exact response of the spring to reductions in groundwater pumping is not known with certainty at this time. Our analysis assumes that the desired outcome is a minimum 10 cubic-feet-per-second flow in Comanche Springs and that this could be achieved by reducing groundwater pumping by 25 percent from recent levels. This is equivalent to an annual reduction of 11,500 acre-feet per year (0.25 x 46,000 acre-feet = 11,500 acre-feet) resulting in annual pumping of 34,500 acre-feet (see Section 9.2 for discussion of the uncertainties with making this estimate). Based on potential overestimation of pumping in the model's calibration, it is possible that the actual amount of pumping reduction needed to achieve no less than 10 cubic feet per second of continuous flow at

Comanche Springs may exceed this value. However, for our purposes, we have used a 25 percent reduction from present day pumping as our target for economic assessment.

10.3 Alternatives for Reducing Groundwater Pumping

We evaluated six different alternatives to reduce groundwater pumping, including (1) leasing full season permits, (2) leasing partial season permits, (3) purchasing permits, (4) improving irrigation efficiency, (5) switching crops, and (6) switching sources. Due to the relationship between spring flow and groundwater pumping, the options are limited to those that affect groundwater pumping from the Edwards-Trinity Aquifer in Management Zone 1.

10.3.1 Leasing Full Season Permits

- Description: Payments to agricultural producers to not use all or a portion of their permit for the duration of the irrigation season (typically February 15th to October 15th).
- Potentially Available Volume: It is likely that this option will be limited to land planted as field crops because the capital investment in pecan trees is significant and pecan trees cannot be fallowed without significant crop loss. There were an estimated 8,354 acres planted as field crops such as alfalfa in 2016. Alfalfa producers reportedly pump 5.5 acre-feet per acre on average during the irrigation season while other field crops have lower water requirements. This analysis applies an average water requirement of 5.0 acre-feet per acre for field crops. To achieve a pumping reduction of 11,500 acre-feet, it would be necessary to enroll 2,300 acres in an annual leasing program. This is approximately 27 percent of the acreage planted as field crops in 2016. We expect a participation rate of 20 percent or less, which results in a potentially available volume of approximately 8,400 acre-feet.
- Estimated Annual Cost: Incentivizing landowners to participate in a full season permit lease will generally require financial compensation above the expected net returns to agricultural production. This analysis applies an expected lease price range of $75 to $150 per acre-foot per year. This is equivalent to a payment of $375 to $750 per acre per year assuming an annual groundwater pumping volume of 5.0 acre-feet per acre. [20]

10.3.2 Leasing Partial Season Permits

- Description: Payments to agricultural producers to not use all or a portion of their permit for part of the irrigation season. This approach is best suited to hay crops whereby agricultural producers can cease irrigation and forego one or more cuttings.
- Potentially Available Volume: It is likely that this option will be limited to land planted to hay, which is estimated to be grown on approximately 4,500 acres. In addition, it is most likely that agricultural producers will enroll older alfalfa stands

[20] Cost range is based upon the estimated net returns to alfalfa and wheat (assuming 3 years of alfalfa followed by 1 year of wheat). The estimated cost is also based on water lease agreements involving alfalfa in other regions of the western United States.

due to concerns over potential yield loss in subsequent years. This analysis assumes that groundwater pumping could be reduced by 2 acre-feet per acre through implementation of partial season agreements. Using a 20 percent participation rate, the potentially available volume is estimated to be 1,800 acre-feet.

- Estimated Annual Cost: The cost for partial season agreements is expected to be similar to full season agreements: $75 to $150 per acre-foot per year. This is equivalent to a payment of $150 to $300 per acre per year assuming an annual groundwater pumping reduction of 2.0 acre-feet per acre.

10.3.3 Purchasing Permits

- Description: Permanent acquisition of all or a portion of a groundwater permit.
- Potentially Available Volume: It is likely that this option will be limited to land planted to field crops or pecan trees that are in decline.
- Estimated Annual Cost: Based upon available information, the value of irrigated cropland in the Trans-Pecos region appears to be relatively low with a reported value range of $1,100 to $2,600 per acre (ASFMRA 2017). However, it is expected that a payment significantly above this range will be needed to incentivize a sale. We are withholding the payment range for permanent acquisition of groundwater permits due to anticipated and ongoing negotiations with owners.

10.3.4 Improving Irrigation Efficiency

- Description: Payments to agricultural producers to incentivize improvements in on-farm irrigation efficiency through installation of soil moisture sensors or conversion from flood to sprinkler or drip irrigation. Low Elevation Sprinkler Application can also be installed on existing center pivots to reduce evaporative losses and improve distribution uniformity.
- Potentially Available Volume: This analysis assumes that the irrigation efficiency on flood and center pivot irrigated fields can be improved by 10 percent with the installation of soil moisture sensors and Low Elevation Sprinkler Application, respectively. On average, this would result in reduced groundwater pumping of approximately 0.5 acre-feet per acre. The total potentially available volume is nearly 2,000 acre-feet if irrigation efficiency can be improved on 33 percent of the actively irrigated land in 2016.
- Estimated Annual Cost: The annual cost is estimated to range from $20 per acre per year for Low Elevation Sprinkler Application installation (including soil moisture sensors) to $50 per acre per year for soil moisture sensors and automated headgates on flood irrigated land. This is equivalent to a cost of $40 to $100 per acre-foot per year assuming a water savings of 0.5 acre-feet per acre.

10.3.5 Switching Crops

- Description: Payments to agricultural producers to convert to a less water-intensive cropping pattern. Typically, this would involve the production of more grain and less alfalfa.
- Potentially Available Volume: We were not able to identify crop water requirements specific to the Pecos County region. Based upon available information, alfalfa evapotranspiration is 5.9 acre-feet per acre compared to 3.0 acre-feet per acre for corn and 3.4 acre-feet per acre for winter wheat (based on information from Borrelli and others [1998]; effective precipitation was not subtracted from the total evapotranspiration estimates). This analysis assumes that replacing an acre of alfalfa with cotton or wheat will reduce groundwater pumping by approximately 2 acre-feet per acre. In 2016, it is estimated that approximately 4,500 acres were planted with alfalfa. Assuming that 25 percent of the alfalfa acreage is replaced by a grain crop, the potentially available volume is 2,250 acre-feet.
- Estimated Annual Cost: The annual cost estimate is calculated as the difference between the net returns to alfalfa and winter wheat (based on average difference between gross revenues less variable costs from 2017 through 2019 using data from Extension Agricultural Economics [2019]). The estimated annual cost is $1,067 per acre per yr. Assuming a water savings of 2 acre-feet per acre, this is equivalent to a unit cost of $534 per acre-foot per year.

10.3.6 Switching Sources

- Description: Payments to groundwater users—both municipal and agricultural producers—to use groundwater from aquifers with less contribution to Comanche Springs. Based upon available information, this could involve, with more study, drilling new wells that tap the Capitan Reef Aquifer.
- Potentially Available Volume: Currently, Groundwater Owner 2 is the only agricultural producer in the region that has a well drilled into the Capitan Reef Aquifer. A test well was drilled into the Capitan Reef Aquifer in a different area of Management Zone 1 as part of a joint initiative between the City of Odessa and the City of Fort Stockton. There continues to be interest in potentially developing the Capitan Reef Aquifer as an alternative supply to the City of Fort Stockton's existing drinking water wells in the Edwards-Trinity Aquifer due to higher water quality in the Capitan. Reported pumping from the existing agricultural well averaged 1,361 acre-feet per year from 2008 through 2016. The modeled available groundwater for the Capitan Reef Aquifer is 11,022 acre-feet per year. With existing permits to the Capitan Reef Aquifer at 1,787 acre-feet per year, there is potentially 9,235 acre-feet per year of available supply from the aquifer.
- Estimated Annual Cost: The estimated cost to drill a well into the Capitan Aquifer is $1 million (Edwards 2019). Assuming an annual yield of 1,361 acre-feet, the average capital cost is approximately $735 per acre-foot. In addition to the capital cost, agricultural producers might need to be compensated for the increased power costs

associated with higher pumping lifts. Using a capitalization rate of 5.5 percent, the estimated annual capital cost is $44 per acre-foot per year. Assuming an additional $100 per acre-foot per year in pumping costs[21], the total annual cost is $144 per acre-foot per year.

10.4 Preliminary Recommendations

The largest potential volume may be achieved through switching sources or purchasing permits while the lowest cost option is improving irrigation efficiency and leasing full season or partial season permits (Table 10.2). In practice, a combination of several of these strategies would probably be employed to achieve pumping reduction goals.

The following provides some preliminary recommendations based upon the available information and analysis presented above.

10.4.1 Phased Approach

The existing groundwater model used by the groundwater conservation district to model spring response to groundwater pumping reductions indicates that reductions in groundwater pumping from the Edwards-Trinity Aquifer will increase flow in Comanche Spring. However, the volume of groundwater pumping reduction from the Edwards-Trinity Aquifer to achieve a specified flow in Comanche Spring is still uncertain. As a result, we recommend that alternatives which can be implemented within a short period of time at the lowest total cost be pursued as a pilot project to test the response in Comanche Springs. These alternatives include full season and partial season leases of permits used to irrigate field crops. The measured response in spring flow during the pilot phase can be used to adjust the targeted pumping reduction using longer-lasting alternatives such as switching sources, increasing irrigation efficiency, and purchasing permits. It may also be possible to achieve a long-term spring flow target by extending full season lease agreements beyond the pilot phase. While this would provide useful information, year-to-year variations in pumping, recharge, and perhaps cross-formational flow still leave hydrologic uncertainty without large decreases in pumping.

10.4.2 Target Wet Water

As described above, a large permitted volume to the Edwards-Trinity Aquifer is unused each year. As a result, it will be necessary to only target permits that are regularly used for irrigation purposes. In addition, it will be important to establish agreements that prevent the presently unused components of these permits from being used to support groundwater pumping. Some potential strategies to address this are:

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[21] According to data provided by the Middle Pecos Groundwater Conservation District, the average Edward-Trinity Aquifer well depth is approximately 300 feet. In comparison, the single well drilled to the Capitan Aquifer is more than 3,000 feet in depth. This estimate assumes that (1) pump lifts to the Capitan Reef Aquifer are 2,000 feet higher than the Edwards-Trinity Aquifer, (2) pump efficiency is 70 percent, and (3) the cost of power is $0.035 per kilowatt-hour.

Table 10.2: Estimated volume and annual cost for each alternative to reduce groundwater pumping.

Alternative	Potential volume (acre-feet)	Annual cost (per acre-foot)
Leasing full season permits	8,400	$75 - $150
Leasing partial season permits	1,800	$75 - $150
Purchasing permits	> 9,200	Redacted
Improving irrigation efficiency	2,000	$40 - $100
Switching crops	2,250	$534
Switching sources	9,235	$144

- Qualify permits based upon recent use history. Qualification may consist of reported groundwater pumping in recent years as well as aerial photo analysis of cropping over the same selected time period. For example, land that has been irrigated in three of the last five years may qualify but land received less frequent irrigation would not qualify.
- Establish land-based agreements that prohibit or limit water application on fields enrolled in the pilot phase and subsequent longer-term agreements.

10.4.3 Pursue Multiple Alternatives

During the pilot phase, it may be possible to achieve a targeted groundwater pumping reduction using a single alternative (such as leasing full season permits). Beyond the pilot, it may be necessary to pursue multiple approaches according to their compatibility with the land use and landowner objectives to achieve a target volume. For example, it is likely that pecan growers not currently contemplating a reduction in acreage will not have an interest in temporary or permanent crop fallowing but may be willing to switch to a groundwater source that is less connected to Comanche Springs.

10.5 Funding Groundwater Conservation in the Comanche Springs Contributing Zone

We evaluated public and private financing resources to enable the alternative to reduce groundwater pumping in the Comanche Springs Contributing Zone. In evaluating the funding resources that would be available for reducing groundwater production in the contributing zone, we looked for grants, subsidized loans, public markets, and private investment opportunities. We evaluated each funding source in the context of its eligibility for capital infrastructure needs (for example, an alternative drinking water supply for the City of Fort Stockton or increasing agricultural irrigation efficiency) and market capitalization needs (for example, for contractual forbearance agreements with agricultural growers or for permanent purchase of groundwater rights). There are a number of funding options available ranging from state and federal funds to local revenues, municipal bonds, and private equity (Table 10.3).

Table 10.3: Summary of funding options for the various conservation options.

<table>
<tr><th></th><th>US Bureau of Reclamation WaterSMART</th><th>US Fish and Wildlife Service Section VI</th><th>Natural Resources Conservation Service</th><th>Texas Water Development Board Agricultural Conservation Program</th><th>Texas Water Development Board State Revolving Funds</th><th>Texas Water Development Board SWIFT Funds</th></tr>
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<tr><th></th><th>Annual Fund Replenished by Pool Revenues</th><th>Annual Fund Replenished by Surface-Water Leasing Revenues</th><th>Municipal Bonds</th><th>Private Equity</th></tr>
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10.5.1 WaterSMART

WaterSMART is a program of the Department of the Interior to advance water conservation and resilient water management across a variety of water user groups. The Department describes the intention of the program to enable "strategies to ensure that this and future generations will have sufficient supplies of clean water for drinking, economic activities, recreation, and ecosystem health." (USDOI 2020). The multi-sector intent of the program makes it one of the most diverse and flexible programs related to water of all federal programs. WaterSMART programs have funded planning activities and infrastructure construction for projects that enhance water reliability.

The program is especially designed to create multi-sector benefits; for example, where projects would enhance resilience for wildlife and industry, municipalities, and farmers.

A typical planning grant to support development of a multi-stakeholder watershed plan is in the $100,000 range; these grants can include time for staff of small watershed groups to manage community stakeholder engagement (USBOR 2020a). WaterSMART's Water Marketing program funds entities with water delivery authority, including water improvement districts and groundwater conservation districts, to develop strategies to establish or expand water marketing activities. The typical grant size ranges from $50,000 to $200,000 (USBOR 2019a). The program also provides funding for infrastructure such as Aquifer Storage and Recovery, groundwater wellfields, and water reuse systems. Infrastructure grant sizes are frequently in the multimillion-dollar range. In 2019, El Paso Water Utilities Public Service Board received $3.5 million of grant funding through the Title XVI Water Reclamation and Reuse Program for a pilot program to treat wastewater to potable reuse standards (USBOR 2019b). Additionally, the program has specific grant programs for water efficiency projects in the municipal, agricultural, and industrial sectors with grant sizes awarded in Fiscal Year 2020 ranging from $300,000 to $1.5 million (USBOR 2020b). Grants typically require at least 1:1 cost share with non-federal money (the exception is for early-stage watershed planning grants). Funding is typically limited to entities with water management authority, such as states, tribal governments, water irrigation districts or groundwater conservation districts. Planning grants can be received by universities or nonprofit entities.

The WaterSMART program's breadth and funding depth makes it an especially interesting resource for deploying infrastructure solutions that may be required for restoring Comanche Springs, especially where those needs fall outside of agriculture. Additionally, the program could be a critical source of funding to support multi-stakeholder planning for restoration of Comanche Springs, including funding for a community-based planning or project coordinator.

10.5.2 U.S. Fish and Wildlife Service Section VI

The Cooperative Endangered Species Conservation Fund (Section 6 of the Endangered Species Act) provides grants to states to enable voluntary conservation projects for candidate, proposed, and listed species. The program is designed to provide funding for species and habitat conservation on non-federal lands. Recipients are required to provide at least a 25 percent match. In Fiscal Year 2016, the U.S. Fish and Wildlife Service awarded about $56 million through the Cooperative Endangered Species Conservation Fund (USFWS 2016). Although this funding is typically used for land acquisition or land management agreements, we have found that there have been some water rights acquired through this fund in the Pacific Northwest. This source of funding could be useful in supplementing other sources of funding from local revenues and federal and state grants aimed at other water users such as agriculture and municipalities. Depending upon the species of benefit, there might need to be assurances that candidate or listed species could be reintroduced into the watershed using Safe Harbor provisions.

10.5.3 Natural Resources Conservation Service

A program of the U.S. Department of Agriculture, the Natural Resources Conservation Service was authorized in the 2018 Farm Bill to deploy billions of dollars a year of conservation assistance to agricultural producers and partners across the country. The Farm Bill authorized $1.75 billion for Fiscal Year 2020 and $1.8 billion for Fiscal Year 2021 for the Environmental Quality Incentives Program, which provides federal cost share of up to 90 percent for on-farm water efficiency upgrades. Alongside the Environmental Quality Incentives Program, the 2018 Farm Bill established $300 million a year for the Regional Conservation Partnership Program (USDA 2019), through which the Natural Resources Conservation Service and its partners help agricultural producers implement conservation activities in priority areas. The Regional Conservation Partnership Program provides 50 percent cost share in a range of on-farm efficiency and water conservation practices and is designed to allow local partner organizations to define scoring criteria to steer federal resources toward priority conservation outcomes.

Conservation groups in other states have leveraged Natural Resources Conservation Service programs to create instream flows. In such an arrangement, a conservation entity may offer to pay the agricultural producer's 50 percent cost share of on-farm efficiency investments to match the federal money. In exchange, the agricultural producer agrees not to pump some proportion of the water conserved through the delivery of on-farm efficiency investments.

10.5.4 Texas Water Development Board Agricultural Conservation Program

The Texas Water Development Board's Agricultural Conservation Program was recently authorized by the Texas State Legislature to receive increased funding. Beginning in 2020, the program will receive $1.2 million a year (twice the resources of prior years). The program is designed to deliver grants to groundwater districts, irrigation districts, and agricultural producers for the costs of water conservation activities including metering, irrigation efficiency systems, and other agricultural conservation activities contemplated in the state water plan. Grants are only available to political subdivisions (which include groundwater districts and irrigation districts).

Although the typical Agricultural Conservation Program grants fund hard infrastructure such as meters, pivots, and soil moisture sensors, other agricultural conservation strategies and best management practices, such as payments to producers to shift toward less water-intensive crops, should also be eligible. Therefore, groundwater forbearance agreements that are executed in exchange for investment in crop switching incentive payments should be eligible for this program.

10.5.5 State Revolving Funds

Texas Water Development Board administers two loan programs with below-market interest rates subsidized by annual U.S. Environmental Protection Agency grants.

The Clean Water State Revolving Fund offers financial assistance for planning and delivery of wastewater, reuse, and stormwater infrastructure. Around $525 million a year is available for Texas communities through this fund with up to $28.6 million in principal forgiveness. Interest rates through the program are between 130 to 165 basis points below market rate for the borrower's underlying credit rating. Loans are available for up to 30 years.

The Drinking Water State Revolving Fund offers around $250 million a year for Texas communities and up to $30 million a year in principal forgiveness. Eligible projects include drinking water infrastructure improvements, including system expansion, distribution infrastructure, development of groundwater wells (including into an alternative resource), and source water protection. Systems that primarily serve low-income customers or which serve 1,000 customers or less or are determined to be of urgent need are eligible for higher levels of principal forgiveness. Interest rates through the program are between 125 to 155 basis points below market rate for the borrower's underlying credit rating. Loans are available for up to 30 years.

The deep subsidies available through these programs make them the most cost-effective resource for financing water infrastructure improvements that would be needed for restoring Comanche Springs. In particular, improvements to the wastewater treatment system at the state correctional facility (the Texas Department of Criminal Justice James Lynaugh Unit)—which operates under a Texas Commission of Environmental Quality permit held by the City of Fort Stockton—could be funded through the Clean Water State Revolving Fund. This would include any distribution infrastructure required to push treated wastewater effluent to the Belding Irrigation Area as a source switch for agricultural irrigation.

Shifting municipal supplies for the City of Fort Stockton and the Pecos County Water Control and Improvement District No. 1 from the Edwards-Trinity Aquifer to an alternative resource like the Capitan Reef Aquifer could be supported through the Drinking Water State Revolving Fund.

10.5.6 State Water Implementation Fund for Texas

The State Water Implementation Fund for Texas was passed by the Legislature in 2013 and approved by Texas voters through a constitutional amendment. Since then, the fund has financed $8.3 billion in water-supply projects across the state. The program was designed to fund any water-supply project with a capital cost, from water infrastructure projects to water conservation, including reuse projects. To be eligible, a project must be in the state water plan, which is updated every five years. However, projects can be included in amendments made to regional plans in the interim.

Financing tools available through the State Water Implementation Fund for Texas include features similar to the state revolving funds described above. However, the fund also includes interesting provisions such as deferred loans, through which principal and interest can be deferred up to eight years or end of construction, whichever is sooner. Interest rate subsidies are dependent upon eligibility for tax-exempt status and the term of the loan (the shorter the loan, the greater the interest rate subsidy), with interest rates subsidies ranging from up to 16 to 35 percent below market rate. Additional interest rate subsidies are available for rural or agricultural water conservation/irrigation projects, up to 50 percent below market rates. Any political subdivision, including cities, counties, water improvement districts, groundwater conservation districts, is eligible for funding through the fund.

The 2017 State Water Plan includes only one project consistent with strategies to restore flow at Comanche Springs. That is a 2020 water management strategy for 6,301 acre-feet per year of agricultural irrigation conservation in Pecos County, with a projected capital cost of $12,287,243 (TWDB 2017a). However, there is also a project in the 2017 plan that would increase production of Edwards-Trinity groundwater in Comanche Spring's contributing zone. This is a 2020 water management strategy for the Pecos County Water Control and Improvement District No. 1 for 250 acre-feet per year of additional Edwards-Trinity Aquifer supplies, with a projected capital cost of $2,456,000 (TWDB 2017b).

10.5.7 Annual Revenues—Pool Entry Fees

As part of this analysis, we evaluated the annual revenues that could be generated by entrance fees paid by non-local visitors to the springs. In this assessment, we assumed that the Comanche Springs Municipal Pool would be reconstructed as a natural spring-fed pool like the one found at nearby Balmorhea State Park (Balmorhea is 54 miles west of Fort Stockton). This comparison seems reasonable, as both springs are within five miles of Interstate 10. Balmorhea is adjacent Route 17, a scenic route connecting travelers on Interstate-10 to Fort Davis, making it a natural stopping point on road trips to the Davis Mountains and beyond. Similarly, Comanche Springs is a mile from State Highway 385, one of the most trafficked routes to Marathon and the Big Bend National Park. That proximity to a well-trafficked tourist route supports our assumption that a restored Comanche Springs could receive a comparable level of visitation and revenues as Balmorhea State Park.

Balmorhea State Park entertained 200,000 non-local visitors in 2014 (Jeong and Crompton 2014). We did not attempt to verify the annual revenues received by Texas Parks and Wildlife Department from park visitation in 2014 or in subsequent years. The following is an estimate of what entrance fees would generate if visitation returns to that level in 2020. With 200,000 visitors a year, the 2020 rates of $7 entrance fee per person (age 13 and above) would simplistically generate $1.4 million in gross revenues at Balmorhea. Assuming a similar level of visitation at Comanche Springs and identical entrance fee for all non-local visitors and assuming a conservative annual budget to maintain the historic bathhouse, pay for staffing, and other costs, we estimated a conservative net revenue of $1 million per year from pool entrance fees at a restored Comanche Springs.

Annual net revenues from Comanche Springs entrance fees could be pledged toward a fund dedicated to maintaining groundwater pumping in the contributing zone for the springs below a critical threshold. If the price of annual or multiyear agreements with agricultural water users in the contributing zone were within the $75 to 100 per acre-foot per year range, this would support annual forbearance agreements for 10,000 to 13,333 acre-feet per year. This range is inclusive of our targeted 25 percent reduction from actual pumping in the Edwards-Trinity Aquifer within Comanche Spring's contributing zone between 2014 and 2018 (11,500 acre-feet per year). Therefore, pool entry fees could meet the entire annual budget for forbearance contracts in Comanche Spring's contributing zone.

10.5.8 Annual Revenues—Tax Revenues from Increased Non-Local Spending

As part of this analysis, we evaluated the economic benefits that could be expected to be generated by restored perennial flows at Comanche Springs. In this assessment, we assumed that the Comanche Springs Municipal Pool would be reconstructed as a natural spring-fed pool like the one found at nearby Balmorhea State Park, as discussed above (Figure 10.5). Jeong and Crompton (2014) estimated that visitation generated $4 million of non-local spending in the surrounding area. These estimated revenues, which included spending on fuel, groceries, and private lodging, did not include park entrance fees (which must be paid to visit the pool) or lodging at the Balmorhea State Park Lodge, which is operated by Texas Parks and Wildlife Department.

The City of Fort Stockton has an existing sales tax of 2 percent and an existing Hotel Occupancy Tax of 7 percent. Assuming no increase in tax rates and that a restored Comanche Springs would similarly yield an additional 200,000 visitors each year to Fort Stockton, an additional $4 million in non-local spending each year would generate an estimated additional $80,000 in annual sales tax revenues. In addition, if 40 percent of visitors to Comanche Springs stay overnight and lodging costs are $150 per night in Fort Stockton, the estimated increased revenue in Hotel Occupancy Tax would be $300,000 per year[22].

Additional future sales tax revenues above a historic baseline could be pledged toward a fund dedicated to maintaining groundwater pumping in the contributing zone for Comanche Springs below a critical threshold. If the price of annual or multiyear agreements with agricultural water users in the contributing zone were within the $75 to 100 acre-feet per year range, this additional $380,000 of annual revenue would support annual forbearance agreements for between 3,800 to 5,067 acre-feet per year. This range is between 33 to 44 percent of our targeted 25 percent reduction from actual pumping in the Edwards-Trinity Aquifer within Comanche Springs' contributing zone between 2014 to 2018 (11,500 acre-feet per year).Therefore, while it could be a component of the overall mosaic of funding sources that could enable Comanche Springs' restoration, it would need to be augmented by other resources.

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[22] This estimate also assumes an average visitor party size of 2.8. This estimate mirrors the estimate of Jeong and Crompton (2014) for Balmorhea State Park visitation patterns.

Figure 10.5: The natural pool at San Solomon Springs near Balmorhea, Texas (photo by Robert Mace, September 14, 2015).

10.5.9 Annual Revenues—Water Sales

In addition, we evaluated the viability of downstream surface water on Comanche Creek being leased as a means of generating revenues that could be dedicated to Comanche Springs' restoration. As part of this assessment, we researched the status of historical surface water rights permitted by the Texas Commission on Environmental Quality. The Pecos County Water Control and Improvement District No. 1 holds all surface water rights on Comanche Creek. The Improvement District's surface-water right, Certificate of Adjudication 23-5456, has two priority dates: March 28, 1913 for diversion for agricultural irrigation and November 1, 1954 for impoundment. The water right authorizes the Improvement District to impound not more than 700 acre-feet a year at a dam in the John H. Herndon Survey 229, Abstract 54 in Pecos County. The water right also authorizes the Improvement District to divert and use not more than 25,205 acre-feet per year. The water right as currently written limits that diversion and usage to irrigation of a maximum of 6,007.61 acres of land within the district's boundary. The dam authorized for impoundment of surface waters may be used for management of flood flows under this permit.

Since Comanche Springs' reliable flow ceased in the 1960s, much of the downspring irrigation infrastructure has eroded. Acreage once dedicated to farming has transitioned to industrial or residential uses or has been fallowed. We did not attempt to classify current land usage in the 6,007.61 acres as defined within the Improvement District's surface-water permit. However, through interactions with various county officials and staff, it became clear that there are unmet non-irrigation water demands within the Improvement District's boundaries which could be met through surface-water sales. Those include residential water needs in both existing and new subdivisions along Highway 18 and FM 1053. The Improvement District has also received requests for recreational water demand for personal amenity ponds and similar features in RV parks. Where the Improvement District cannot satisfy those demands, water users have sought to drill new groundwater wells into the Edwards-Trinity and Pecos Valley aquifers. Most of the current and anticipated residential users intend to supply water to their homes in subdivisions with lots smaller than 10 acres. On a lot 10 acres or smaller, the landowner must secure groundwater permits to drill and produce groundwater because they do not meet the statutory groundwater permitting exemption. Demand for potentially dozens of those wells has resulted in public discussion at the Middle Pecos Groundwater and Conservation District regarding the potential for substantial local well interference and aquifer drawdown.

In addition to these recreational and residential demands, Pecos County has also experienced significant demand for industrial water for completion of oil and gas wells. This type of use has been satisfied by other irrigation districts in the Pecos River Basin through amendment of surface water permits to include industrial usage as a beneficial use.

Currently, without an amendment to the Improvement District's surface-water permit, none of these demands—municipal, recreational or industrial—could be satisfied using flows from Comanche Creek, even if perennial flow were achieved. The following discussion of revenues that could be dedicated from surface-water leases for these purposes assumes that the Improvement District would file a permit amendment to the Texas Commission on Environmental Quality to add municipal, recreational, instream flow, and industrial uses to its surface-water permit. Doing so would authorize the Improvement District to market its surface water for non-irrigation purposes consistent with those authorized uses. Additional amendments to the permit may be required, such as amendment of the authorized diversion point. We did not attempt to undertake a specific analysis of the diversion point amendment that may be required to allow its water to be marketed for non-irrigation purposes.

A perennial flow rate of 10 cubic feet per second at Comanche Springs, the estimated value to allow recreational contact with spring water at a restored Comanche Springs pool) is equivalent to roughly 7,240 acre-feet per year. Assuming that all of that surface flow was diverted for sale by the Improvement District downstream of Comanche Springs at a unit rate of $75 per acre-foot, the annual revenue would be $543,000. This is an extremely coarse assumption but is reflective of the traded value of water for agricultural and municipal uses in the region (for municipal uses, not inclusive of costs related to treatment, storage or delivery to point of use). This price clearly does not track the price paid for water by oilfield buyers, which, according to industry interviews conducted by Texas Water Trade, has ranged from $.10 to $.50 per barrel in Pecos County (an acre-foot is equal to about 7,758 barrels, making that unit cost range from $775 to 3,879 acre-feet per year). However, while opportunities for spot market or contract sales for oilfield water demands have created significant revenue generation for some irrigation districts in the Pecos River Basin, the service territory of the Improvement District is somewhat removed from the heart of oil and gas activity in the Permian Basin. In addition, the substantial volume of produced water from oil and gas wells in the basin make the longer-term commercial outlook for freshwater sales less bullish than in the recent years. For this reason, we did not estimate potential revenues from oilfield demand, and instead hewed to municipal and agricultural prices for revenue forecasting.

Annual net revenues from surface-water sales could be pledged toward a fund dedicated to maintaining groundwater pumping in the contributing zone of Comanche Springs below a critical threshold. If the price of annual or multiyear agreements with agricultural water users in the contributing zone were within the $75 to 100 per acre-foot range, the estimated $543,000 in annual surface water sales would support annual forbearance agreements for between 5,430 to 7,240 acre-feet per year. This range is between 47 to 63 percent of our targeted 25 percent reduction from actual pumping in the Edwards-Trinity Aquifer within Comanche Springs' contributing zone between 2014 and 2018 (11,500 acre-feet per year).Therefore, while it could be a component of the overall mosaic of funding sources that could enable Comanche Springs' restoration, it would need to be augmented by other resources.

10.5.10 Municipal Bonds

Whether reductions in groundwater pumping in Comanche Springs' contributing zone were achieved through short-term leasing agreements, permanent groundwater rights purchases, or some combination thereof, the upfront cost of securing these agreements is likely to exceed the annual revenues that would be generated through the spring's restoration (including revenues from pool entrance fees, non-local spending and surface water sales). However, the annual returns could on their own be sufficient to support an entirely market-based restoration of the springs. How can this be so? The answer lies in securitization.

Securitization of future revenues is a standard feature of American infrastructure finance. It is used to build roads (from public access to privately financed toll roads), schools and water systems. Securitization simply means that future revenues (road toll payments, tax payments, enterprise revenues from water sales) are pledged as repayment to the investors whose capital pays for the infrastructure to be built. In the case of municipal bonds, investors provide their capital by purchasing bonds sold by cities, counties, or special purpose districts with taxation or revenue authority. Pecos County, the City of Fort Stockton, and the Pecos County Water Control and Improvement District No. 1 all have revenue streams that could be pledged as repayment for bonds that could be issued for the near-term costs of restoring Comanche Springs.

Assuming that the annual revenues of non-local spending, pool entrance fees, and water sales created by a restored Comanche Springs were at almost $2 million (Table 10.4), how much debt could be issued today if these local revenues were pledged to that debt's repayment?

Table 10.4: Estimated pledgeable revenues from non-local visitation to Comanche Springs.

Revenue source	**Estimated annual revenue**
Sales tax	$80,000
Hotel occupancy tax	$300,000
Pool entrance fees	$1,000,000
Surface water sales	$543,000
Total new revenues	**$1,923,000**

If these revenues were pledged against a municipal bond with a 30-year term issued at an interest rate of 2.32 percent,[23] these new revenues could secure a $32 million bond. Let's imagine that this 30-year revenue bond were funded through the Texas Water Development Board at a subsidized rate of 1.07 percent. In that scenario, a $45 million bond could be issued.[24]

It is common for special purpose entities to be formed to issue debt for projects that are repaid through multiple revenue sources that cross political subdivisions. Such a special purpose entity could theoretically be created for Comanche Springs' restoration, leveraging pledged revenues from the county, city and water district. Alternatively, specific revenues from other political subdivisions can be pledged through interlocal agreements to an existing entity (for example, the City of Fort Stockton could pledge additional sales tax revenues from non-local visitation to a bond issued by Pecos County through an interlocal agreement).

10.5.11 Outcomes-Based Bonds

Typically, bonds are structured with a payment schedule of fixed interest rate payments and principal repayment. In recent years, outcomes-based bond financing has emerged as a tool for enabling investments in projects with untested or uncertain results. The core benefit of outcomes-based financing is that project sponsors can transfer some of their project risks to investors.

One of the most recognized examples of an outcomes-based bond is DC Water's $25 million Environmental Impact Bond, which allowed the urban water and wastewater utility to fund installation of green stormwater infrastructure as a component of its strategy for managing Combined Sewer Overflows. Unlike a typical bond issuance, DC Water's Environmental Impact Bond was designed with a flexible interest rate payment to investors that was based upon the performance of a pilot round of green stormwater infrastructure in retaining rainfall. If the green stormwater infrastructure met predefined performance metrics for rainfall

[23] Assumes a 30-year tax-exempt issuance using the Thomson Reuters Municipal Market Data yield curve for AA-rated entities, as of March 17, 2020. Also assumes a debt service coverage ratio of 1.3.

[24] Assumes a 30-year tax-exempt issuance using the TWDB's Drinking Water State Revolving Fund non-equivalency interest rate for AA-rated entities as of March 17, 2020. Also assumes a debt service coverage ratio of 1.1.

retention, interest payment to investors for the five-year private placement bond would be set to market rate. If the green stormwater infrastructure's performance outperformed the predefined performance metrics, DC Water agreed to pay investors a higher interest payment than the market rate. Conversely, if the green stormwater infrastructure underperformed its predefined performance metrics, the interest payment due to investors would be substantially below market rate, thereby offsetting the cost of other constructed interventions that DC Water would be required to undertake to meet stormwater management regulations. DC Water's Environmental Impact Bond was sold in a private placement to Goldman Sachs (Qualified Ventures, undated).

DC Water's Environmental Impact Bond was structured with Quantified Ventures, an outcomes-based capital firm that has supported issuance of more than a dozen other outcomes-based bonds for other communities across the country. Like the DC Water Environmental Impact Bond, most of these issuances have been designed with the interest payment being the only performance-dependent element of the structure. However, a performance-based bond that Quantified Ventures has designed to support development of a mountain biking trail system in Ohio offers an interesting model for an outcomes-based model that could be deployed to manage risks associated with the restoration of Comanche Springs. Quantified Venture's Ohio performance-based bond adjusts the interest payment owed to investors based upon predefined performance metrics (in this case, metrics are framed around tourist visitation to the mountain biking trail system funded by the bond). Unlike the DC Water's Environmental Impact Bond, the Ohio outcomes-based structure also includes an element of principal forgiveness if the project fails to achieve these predefined performance metrics. This design was crucial for the Ohio communities supporting development of the mountain biking trail, as their current economic condition makes investment in speculative tourist infrastructure a relatively high financial risk. While this performance-based principal repayment agreement is highly unusual in the municipal finance world, it is routinely used in the insurance and reinsurance industries, which use catastrophe bonds to secure capital for high-loss, low-probability events like hurricanes and earthquakes.

Local jurisdictions with bonding authority such as Pecos County and the City of Fort Stockton could leverage performance-based bonds featuring principal forgiveness to manage the risk of investing in Comanche Springs' restoration. For example, some combination of pool entrance fees, sales tax, hotel occupancy tax and surface water sales revenues could be pledged against repayment of a performance-based bond to fund groundwater leases, rights purchases and/or other infrastructure needs associated with the spring restoration. That performance-based bond could be structured such that some or all principal is forgiven if flows at Comanche Springs fall below a predefined flow rate for a predefined period of time. A higher interest rate may be expected by investors accepting the risk of principal loss, but this higher interest rate may be acceptable to the local issuer as a means of shielding local taxpayers from the risk of project failure. Although such an outcomes-based structure has not been underwritten to date by the Texas Water Development Board, its market position as a private buyer of local debt and its ability to offer lower-than-market interest rates would make it an interesting prospective buyer for such a product.

10.5.12 Private Equity

Equity investors receive an ownership position in a venture or asset. There are multiple hypothetical arrangements through which equity investors could advance Comanche Springs' restoration.

One of these is through acquisition of active agricultural land and associated groundwater rights in the spring's contributing zone. Some equity investment firms specialize in acquisition of agricultural operations. Such entities may acquire a farm and generate investment returns through reoperation of the agricultural enterprise, capitalizing on returns from higher revenue crop types than were grown on the farm historically. Additional returns may be generated through a transition to dryland farming or investment in precision irrigation systems. Where there are active water rights markets, water conservation enabled through such on-farm improvements could be monetized through sale or lease of water rights no longer needed for agricultural irrigation to other municipal, industrial or environmental buyers. Existing crop types and irrigation systems in Comanche Springs' contributing zone could create an opportunity for such equity investors, who may additionally be enticed by groundwater leasing payments capitalized by pool entrance fees, sales and hotel occupancy taxes and other revenue sources.

Equity investors specializing in infrastructure projects could provide capital to fund development of source switch infrastructure (for example, municipal groundwater wells and delivery pipelines to replace current demand on the Edwards-Trinity Aquifer). In that example, equity investors could receive revenues from municipal water sales for a period of time under contract with the City of Fort Stockton and the Pecos County Water Control and Improvement District No. 1. Like San Antonio Water System's Vista Ridge Project, such a long-term contract could allow for the infrastructure to transfer ownership at a set future date to the municipal beneficiary. Additionally, the municipal beneficiary can be given right of first refusal for continuing the water sales contract at the end of the initial contract period.

The benefit of an equity arrangement for infrastructure development is transfer of construction and performance risks to the equity investor and operator. For complex infrastructure projects, this can be highly advantageous for a municipal beneficiary without the operating revenue or the in-house expertise to plan and deliver an infrastructure project. The cost of transferring this risk to the equity investor and private project developer is a higher capital cost than what would be incurred through municipal utility finance (whether market-rate or state-subsidized programs like those managed by the Texas Water Development Board).

Although equity investors typically hold an ownership position in underlying physical assets, investments can be structured such that the investor is only entitled to the revenue stream resulting from the investment, and not the underlying assets (for example, the water rights or pipeline). The relatively higher cost of equity capital compared to debt capital would drive consideration of whether the other risk management benefits of equity investment would justify this route compared to a municipal debt play.

10.6 Leveraging These Sources

The restoration of Comanche Springs could—and likely would—be enabled through a blending of these various financial resources. This resource blend is sometimes referred to as a capital stack, although often that phrase is used in reference to the layers of capital that are recruited for a specific project such as a water infrastructure project.

What makes the restoration of Comanche Springs viable is the multiple economic and ecological benefits that restored surface flows would achieve. Those benefits include recreational tourism spending, increased surface water availability, habitat restoration for endangered species and cultural amenity enhancement for local residents. While not all of these benefits create a direct revenue stream that could be tapped to fund the project, many of them do. For this reason, project sponsors would be right to think of restoring Comanche Springs primarily as an economic development project.

Capturing the opportunity to affect a market-based restoration of Comanche Springs would require a consistent, coordinated effort among a patchwork of political subdivisions. These include Pecos County, the City of Fort Stockton, Pecos County Water Control and Improvement District No. 1, and the Middle Pecos Groundwater Conservation District.

11.0 Groundwater Export.

As we were completing the study and finishing this report in mid-May, Midland, San Angelo, and Abilene—all part of the West Texas Water Partnership—approved an interlocal agreement on May 12th to implement a $260 million agreement with Fort Stockton Holdings for 28,400 acre-feet of water from the Leon-Belding Irrigation Area through at least 2070 (Burch 2020, Doreen 2020, Tufts 2020). The deal results in 15,000 acre-feet per year for Midland, 8,400 acre-feet per year for Abilene, and 5,000 acre-feet per year for San Angelo (Burch 2020) and requires the construction of a well field, a pipeline, and treatment estimated to cost $300 million (Tufts 2020). The take-or-pay contract—the full volume of water is paid for whether it is used or not—requires the payment of $0.3425 per 1,000 gallons through 2029, $0.55 for 2030, and then 0.5 percent annual increase through 2070 (Doreen 2020). The cities have the option of extending the contract until 2090 and then until 2110 (Doreen 2020).

Abilene would pay for its allocation of water but swap it for Midland's water in O.H. Ivie, thus avoiding having to build a pipeline to its location (Bethel 2020; although the city would need to work with the Colorado River Municipal Water District to reverse flow from Midland such that Midland could deliver the water to Abilene in the event O.H. Ivie dried up, something it threatened to do in May of 2014 when it was only 10.7 percent full). Abilene and San Angelo would also share in the cost of building the pipeline from the Leon-Belding Irrigation Area to Midland (Bethel 2020). Abilene's mayor noted that the city may not build the Cedar Ridge reservoir with the groundwater in hand (Bethel 2020).

It is interesting to note that the unit price of water secured through this contract is within the range we had estimated using the value of crops currently irrigated in the Leon-Belding Irrigation Area.

12.0 Recommendations

There is additional work and analysis to be done on the historical, hydrogeologic, policy economic fronts to refine our analyses, but also strategies that can be advanced now to achieve year-round flow at Comanche Springs.

12.1 Hydrohistory

Recommendations on refining the hydrohistory involve researching pre-1920 flow measurements at Comanche Springs and researching flow data at Leon Springs.

12.1.1 Research the pre-1920 flow measurements

The U.S. Geological Survey made two measurements of springflow before any high-volume wells were drilled in the Leon-Belding area, including those drilled at Leon Springs to increase flow. Water budgets for 1920, 1958, and 2012–2016 that include Leon Springs and associated wells and Comanche Springs do not agree with these earlier measurements. Sharp and others (1991) noted that pre-1920 data are less reliable but without explanation (the fact that the measurement for 1899 uses “Summer” for the date of measurement is concerning). We recommend a deeper investigation of where these measurements were made and the error bars associated with them. Setting aside the double-accounting, the groundwater model by Harden and others (2011) uses these flow measurements to define the upper limit of springflow at Comanche Springs, so the impact of these measurements—which appear to be 10 cubic feet per second higher than subsequent water budgets would suggest—could be substantial for the sustainable development of the resource and for assessing the pumping reduction needed to maintain year-round springflow at Comanche Springs.

12.1.2 Research Leon Springs flow data

The only data we were able to find on Leon Springs were the water-year summaries in Brune (1975) and Brune (1981). Brune (1975) tantalizingly reports a maximum daily flow rate for the record, suggesting that he located daily data for the springs, something we were not able to do. We recommend additional research to locate this data, which would provide information on the seasonality of flow at the springs as well as additional calibration data for groundwater modeling.

12.1.3 Research the history of the Improvement District including the history of wells in its jurisdiction

We were not able to find much information about the history of the Pecos County Water Control and Improvement District No. 1. As part of a study of the hydrogeology of its jurisdiction (discussed later), it would be good to better understand more about the formation of the District and the well drilling that occurred over time in its jurisdiction.

12.2 Hydrogeology

Recommendations on refining the hydrogeology involve monitoring springflow at Comanche Springs, estimating the proportion of flow from old and young water, revisiting the pumping estimates, researching the hydrogeology north of Interstate-10 in Comanche Creek, increasing the resolution of stress periods in the model, revising pumping and recharge in the model, and developing a lumped-parameter model of the flow system.

12.2.1 Continuously monitor springflow at Comanche Springs

With Comanche Springs now returning during the winter months over the past 10 years, we recommend installing a real-time monitoring station at the springs. This will not only help with better understanding the flow system, but also provide valuable data to calibrate and verify the groundwater model as well as monitoring future effects on springflow—both increases and decreases—over time.

12.2.2 Estimate the proportion of young and old water in the aquifer

Geochemical studies have revealed both old and recent water in the aquifer in the study area; however, there's not yet been an attempt to use this geochemical data to estimate the relative volumes of the young and old water. We recommend conducting this analysis since it will better inform the conceptual model of groundwater flow in the area resulting in better models in the future.

12.2.3 Revisit pumping estimates

Pumping estimates by Harden and others (2011) appear to be too high and, during the critical period when the springs first went dry during the 1950s, not correlate as well as they should with water levels in the area. Furthermore, water budgets based on springflow and pumping in 1920, 1958, and 2012–2016 suggest that not only are the pumping estimates too high, but inflows into the Leon-Belding Irrigation Area (recharge plus cross-formational flow) are as well.

Due to non-uniqueness issues, especially when the water budget is not constrained, a variety of groundwater models that accurately simulate water levels and springflows can be generated for a variety of recharge rates and pumping levels. This is particularly the case in karst aquifers where, due to scaling, hydraulic conductivity can vary orders of magnitude. A model biased by high pumping and inflow estimates will indicate that pumping can be higher than reality to achieve sustainability, whether the springs are flowing or not. Higher pumping estimates actually help the economics of using water markets to achieve year-round flow, but we are more interested in being accurate than having falsely achievable goals.

12.2.4 Research the hydrogeology of Comanche Creek north of Interstate-10

While researching the hydrohistory of the area, we discovered that a number of other springs flowed downstream of Comanche Springs. Interestingly, these springs went dry about the same time Comanche Springs went dry. We assumed in this report that these springs did not have a direct connection (that is, through the Edwards-Trinity Aquifer) to the Leon-Belding/Comanche Springs flow system, a conclusion supported, in part, by our water budget analysis. Veni (1991) speculated that Pleistocene sediments deposited in Comanche Creek capped the original primary discharge point with lower-permeable sediments, raising water levels and creating Comanche Springs. This suggests that there may be a direct hydrologic connection between Comanche Springs and the area downstream. It's unclear if the original primary discharge point or other buried springs were or are still flowing at some level. We recommend a full hydrogeologic study of this area to better understand its connection to Comanche Springs and the broader Edwards-Trinity Aquifer flow system. A visit to these lower-elevation springs when Comanche Springs is flowing could provide important clues to the connectivity of the flow system.

12.2.5 Increase the resolution of stress periods in the model from annual to monthly

With annual stress periods in the model, it's not possible to assess seasonal variations in water levels or springflows. Bill Hutchison is currently working with the Middle Pecos Groundwater Conservation District to make this improvement. We support this work.

12.2.6 Revise pumping, recharge, and inflow in the model

Based on the recommendations above and other findings in this report, the model should also be revised to reflect more accurate assessments of pumping and recharge, when available. Geochemical data collected since the development of the Harden and others (2011) model suggests that most of the flow through the system is from cross-formational flow and not local recharge, so the model should be revised to more accurately represent the source of water to the system.

12.2.7 Develop a lumped parameter model

The sub-regional models developed thus far may be more complicated than they need to be to simulate flow in the system. Based on a simple water budget approach—basically a bathtub model—we achieved a balanced water budget under three different production scenarios, suggesting that a far simpler modeling approach would work for the system. For example, Wanakule and Anaya (1993) used a lumped-parameter model—a fancy bathtub model—to accurately simulate water levels and springflows in the San Antonio Segment of the Edwards Aquifer.

12.2.8 Evaluate the potential effects of a warming climate on the system

Once a better understanding of where the water is coming from in the system is attained, it may be important to evaluate how a warming climate may impact the water budget, which will impact sustainable management of the aquifer as well as flow at the springs. Given than geochemical data suggests much of the inflow is from cross-formational flow, this may not be as important. Nonetheless, it would be good to investigate this potential threat to long-term maintenance of water levels and springflows.

12.2.9 Assess springflow at Diamond Y Springs

Veni (1991) found much different spring flows at Diamond Y Springs than previous measurements, which begs the questions (1) what has been measured where in these springs? and (2) what are the accurate measurements of the springs? Flow at Diamond Y Springs may not be important to the question of pumping in the Leon-Belding Irrigation Area and flow at Comanche Springs, but it may help to discern flow out of the Leon-Belding Irrigation Area through the Edwards-Trinity Aquifer. A better understanding of Diamond Y Springs may also inform a better understanding of the flow dynamics between the Rustler Aquifer and Leon and Comanche springs.

12.2.10 Evaluate the composite hydrograph for the Leon-Belding Irrigation Area

We like the concept of the composite hydrograph for the Leon-Belding Irrigation Area developed by Harden and others (2011) because, similar to springflows, it offers clues to pumping volumes in the system. Harden and others (2011) do not provide a detailed assessment of how the hydrograph was assembled—it would be helpful to reconstruct it, document the process, and evaluate it, especially with respect to springflow and, ultimately, pumping.

12.3 Water Market

Recommendations on water markets include establishing a leasing market for agricultural water, identifying an alternative aquifer for Management Zone 1, evaluating locations for aquifer storage and recovery projects, amending surface-water rights to enable a broader array of uses, and forming a special purpose entity to fund spring restoration.

12.3.1 Establish a leasing market for agricultural water

A multi-year market to enlist agricultural irrigators in voluntary forbearance in Management Zone 1 is paramount to testing Comanche Springs' response to groundwater production. Establishing this market before municipal export commences will provide critical data to right-size total pumping in Management Zone 1 as demands evolve over time. This program would also inform the capacity needed in alternative aquifer formations or in an aquifer storage and recovery project to augment supplies in the Edwards-Trinity Aquifer. Texas Water Trade has raised $300,050 to establish such a pilot market from the National Fish and Wildlife Foundation and its oil and gas partners in the Pecos Watershed Conservation Initiative. Texas Water Trade will bring another $1.1 million in U.S. Department of

Agriculture funding to provide incentives for on-farm efficiency improvements to establishment of this market.

12.3.2 Identify most-preferred alternative aquifer in Management Zone 1

Numerous stakeholders in Management Zone 1 have an interest in diversifying beyond the Edwards-Trinity Aquifer. Both the Rustler and the Capitan Reef aquifers were cited by groundwater users as alternative formations of interest. However, as discussed in this report, the Rustler Aquifer appears to be a significant contributor to flows at Comanche Springs through inflows to the Edwards-Trinity Aquifer. The Capitan Reef Aquifer may be the more preferred aquifer for offsetting production from the Edwards-Trinity Aquifer in Management Zone 1, although depth to water makes wells in the Capitan Reef Aquifer a major capital undertaking.

The Middle Pecos Groundwater Conservation District can play an important role in enabling sustainable alternatives by funding studies to test interaquifer communication within Management Zone 1. Funds recently raised by Texas Water Trade from the Bureau of Reclamation can advance some of this understanding, but more resources will be required to support improved decision making. With better information, the groundwater conservation district can also play a role in recruiting subsidized public funds to establish alternative wells.

12.3.3 Evaluate appropriate locations for aquifer storage and recovery

Municipal demand from the City of Fort Stockton and other regional water users cannot be temporarily suspended (although municipal water conservation measures to lower overall demand in the Edwards-Trinity Aquifer should not be discounted). Aquifer storage and recovery may be a needed long-term investment to support municipal and agricultural demand while sustaining year-round springflow. Because achieving a minimum flow of 10 cubic feet per second may require average annual flow of 20 cubic feet per second, there is potential for excess groundwater in the Edwards-Trinity Aquifer to be stored and then retrieved from the Rustler Aquifer during the winter months. The Middle Pecos Groundwater Conservation District can advance understanding of the most suitable formations and locations for aquifer storage and recovery in the region. As with other capital projects and agricultural efficiency efforts discussed herein, these projects should be incorporated into the Region F Water Plan to ensure that subsidized funding from the Texas Water Development Board can be brought to bear.

12.3.4 Amend surface water rights on Comanche Creek to enable a broader array of uses

The Pecos County Water Control and Improvement District No. 1 holds all permitted surface water rights on Comanche Creek. Currently its permit allows diversion of those waters only for flood control and irrigation. Adding a variety of beneficial uses—including municipal, industrial and instream flows—would entitle the Improvement District to be more flexible in its water use, including sales of that water for revenues that could be pledged to springflow restoration.

12.3.5 Form a special purpose entity to fund spring restoration

A substantial proportion of the capital cost of spring restoration could be funded through securitization of springflow-related revenues. For example, some combination of pool entrance fees, sales tax, hotel occupancy tax and surface water sales revenues could be pledged against repayment of a performance-based bond to fund groundwater leases, rights purchases and/or other infrastructure needs associated with the spring restoration.

It is common for special purpose entities to be formed to issue debt for projects that are repaid through multiple revenue sources that cross political subdivisions. Such a special purpose entity should be formed to lay the groundwork for Comanche Springs' restoration. This special purpose entity could include representation by Pecos County, the City of Fort Stockton, Pecos County Water Control and Improvement District No. 1, and the Middle Pecos Groundwater Conservation District.

Having this entity in place would steward a collective purpose among these disparate constituencies. It would also create the concentrated economic heft needed to realize Comanche Springs' restoration as an economic development project.

12.4 Policy

Recommendations on refining the policy involve removing the South Coyanosa Springs area from Management Zone 1, capping permits instead of pumping, and setting desired future conditions for the management zones.

12.4.1 Remove the South Coyanosa Springs area from Management Zone 1

The hydrogeology of the area strongly suggests that the South Coyanosa Springs area is not part of the Leon-Belding Irrigation Area flow system. Including this area in Management Zone 1 potentially confuses how much water is available for pumping and how much is being pumped to preserve sustainable pumping (and thus springflow) in the Leon-Belding Irrigation Area. We recommend that the Middle Pecos Groundwater Conservation District consider removing the South Coyanosa Springs area from Management Zone 1.[25]

12.4.2 Consider limiting permits rather than pumping

At present, the district's rules allow permits to exceed the modeled available groundwater volume, theoretically resulting in no limit to the number of permitted amounts. For a water market to preserve springflow, there needs to be a limit to the permitted amounts to ensure that purchased and then retired permits result in reduced pumping. An alternative approach to handling production permits would be to connect production limits to surface acreage similar to how the Guadalupe County Groundwater Conservation District permits its groundwater use (Blumberg and Collins 2016). Success in increasing spring flows would raise water levels which could open more land in the Leon-Belding Irrigation Area to potential production. There will also be a risk of someone sinking a well into the flowpath between the Leon-Belding Irrigation Area and Comanche Springs to intercept flow. A correlative approach such as the

[25] As we were going to press, the groundwater district removed the Coyanosa area from Management Zone 1.

Guadalupe County Groundwater Conservation District's may prevent springflow gains from being recaptured and further protect historic and existing use permits.

12.4.3 Set desired future conditions for management zones and use the sub-regional model to evaluate the modeled available groundwater volumes instead of the regional model

As previously discussed, the state-recognized groundwater availability model for the Edwards-Trinity Aquifer is not appropriate for evaluating the desired future condition for Management Zone 1. Therefore, we recommend that the district seek to establish desired future conditions for its management zones and then work with the Texas Water Development Board to use the appropriate local model(s) to evaluate the modeled available groundwater volumes. The desired future condition could also be set to maintain springflows at Comanche Springs, but that would likely raise investment backed expectation concerns and result in petitions and lawsuits. Our approach for this project has been to promote a market-based-solution for win-win solutions.

12.4 Next Steps

We believe the next steps involve a multi-pronged approach, some of which is already in process. For example, Texas Water Trade has already raised funds to establish a pilot market and to incentivize on-farm efficiency improvements, and the Middle Pecos Groundwater Conservation District is improving the Harden and others (2011) model (although our report may prompt additional changes). Given the importance of pumping estimates, not only to estimating the amount of pumping needed to maintain year-round springflow but also to groundwater resources in Management Zone 1, we strongly recommend a thorough analysis of pumping in the Leon-Belding Irrigation Area, especially since the model is currently being updated and the values in the model overestimate pumping. The groundwater district should also install a pressure transducer in the spring canal to acquire real-time flow measurements using the rating curve developed by Norris and Opdyke (Appendix A). These measurements not only provide flow at Comanche Springs, but also serve to check pumping estimates. Finally, the groundwater district should explore what it may be willing to do to limit permitted volume.

13.0 Conclusions

We undertook a study to evaluate the hydrohistory, hydrogeology, policy, and economics of bringing back year-round flow to the historic Comanche Springs. While there have been a number of hydrogeologic studies conducted over the past 70 years, this is the first to fully assemble the hydrohistory of the flow system and evaluate the policy and economics of bringing back year-round flow.

By evaluating historic hydrogeologic reports and newspaper accounts of the development of spring-fed irrigation at Leon and Comanche springs and pump-fed irrigation in the Leon-Belding Irrigation Area, we compiled the most comprehensive, quantified timeline of known hydrologic events for the flow system. Most importantly, we rediscovered the flow-enhancing wells drilled at Leon Springs between 1915 and 1916 and reconstructed, through newspaper reports and analysis, how much these wells enhanced flow at the springs. This rediscovery has implications for the system's water budget as well as estimates of pumping and recharge in the numerical groundwater flow models and hypotheses about the long-term equilibrium of the regional flow system. A systematic analysis of historical estimates of pumping and springflows reveals that the groundwater model currently used to make management decisions overestimates pumping by about 50 percent and that a simple water budget approach can be used to explain the system and, in turn, estimate pumping when there is flow at Comanche Springs.

The Middle Pecos Groundwater Conservation District describes its mission as helping to "…maintain a sustainable, adequate, reliable, cost effective and high-quality source of groundwater to promote the vitality, economy and environment of the District." The district's rules include aquifer-based production limits based on achieving the desired future conditions of aquifers in the district, including within management zones, one of which encompasses the flow system for Comanche Springs. The district's current management approach, while seeking to achieve sustainability, is not amenable to creating a water market to maintain springflows because, overall, while pumping is limited, permits are not.

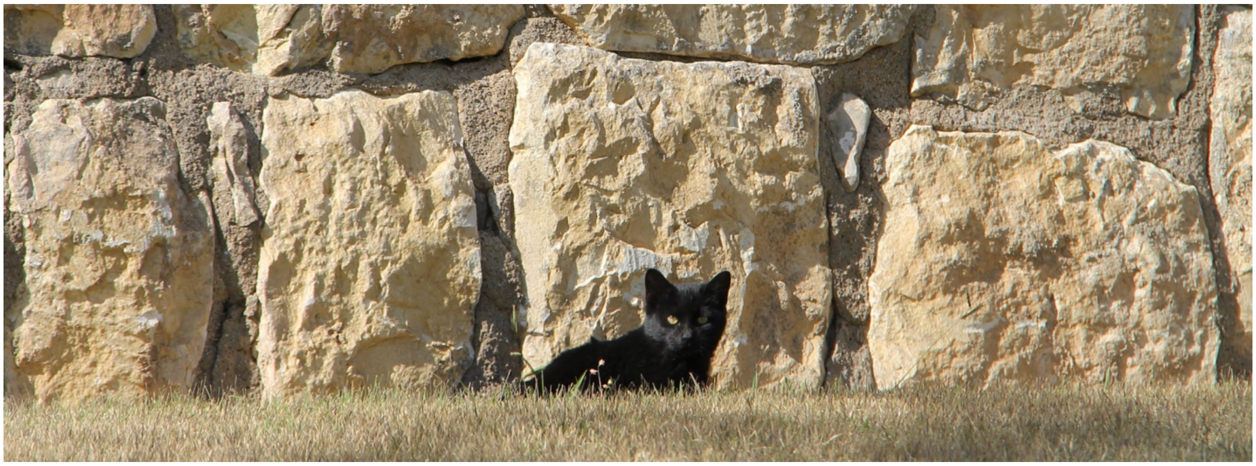
Based on results of a topographic survey we conducted, state code on turnover in pools, and nearby spring analogues of flow needed for endangered fish species, we estimated that flow at

Comanche Springs needs to be above 10 cubic feet per second for the natural pool to meet health and human safety and species requirements. Because of seasonal variations due to irrigation pumping, we determined that average annual springflow needs to be 20 cubic feet per second. Using a variety of methods, we identified that pumping needs to be between 26,000 to 35,000 acre-feet per year (with the lower number more likely).

We evaluated six different alternatives to reduce groundwater pumping. Leasing full season permits could reduce pumping by 8,400 acre-feet per year at a cost of $75 to $150 per acre-foot. Leasing partial season permits could reduce pumping by 1,800 acre-feet per year at a cost of $75 to $150 per acre-foot. Improving irrigation efficiency could reduce pumping by 2,000 acre-feet per year at a cost of $50 per acre-foot. Switching crops could reduce pumping by 2,250 acre-feet per year at a cost of $1,067 per acre-foot. Switching sources could reduce pumping in the Edwards-Trinity Aquifer by 9,235 acre-feet per year at a capital cost of $735 per acre-foot and an annual operating cost of $144 per acre-foot. Purchasing permits could reduce pumping by more than 9,200 acre-feet per year; we did not identify a cost for this alternative due to on-going negotiations.

We also identified funding sources to implement the alternatives, including WaterSMART, U.S. Fish and Wildlife Service Section VI, Natural Resources Conservation Service, Texas Water Development Board Agricultural Conservation Program, state revolving funds, State Water Implementation Fund for Texas, pool entry fees, tax revenues from increased non-local spending, water sales, municipal bonds, outcomes-based bonds, and private equity. The restoration of Comanche Springs could—and likely would—be enabled through a blending of these various financial resources. What makes the restoration of Comanche Springs viable is the multiple economic and ecological benefits that restored surface flows would achieve. Project sponsors would be right to think of restoring Comanche Springs primarily as an economic development project. Total pledgeable new revenues from non-local visitation to Comanche Springs could amount to $1.9 million.

We believe the next steps involve a multi-pronged approach, some of which is already in process, such as establishing a pilot market, incentivizing on-farm efficiency improvements, and improving the groundwater model. Given the importance of pumping estimates, not only to estimating the amount of pumping needed to maintain year-round springflow but also to groundwater resources in Management Zone 1, we strongly recommend a thorough analysis of pumping in the Leon-Belding Irrigation Area, especially since the current model is calibrated with overestimates of pumping and is currently being updated. The groundwater district should also measure spring-flow in real-time to not only have flow for Comanche Springs but also serve to check pumping estimates. Finally, the groundwater district should explore what it may be willing to do to limit permitted volume.



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Appendix A

Estimation of Seasonal Discharge (2008–2010) from the Formerly Perennial Comanche Springs

While conducting this study, we discovered that Chad Norris and Dan Opdyke of the Texas Parks and Wildlife Department had written an unpublished paper on work they did analyzing the dynamics of historical flows at Comanche Springs and developing a modern rating curve for flow from the springs. They graciously agreed to allow us to include the main part of their paper in this appendix since we used their rating curve to estimate springflow at the springs and used their data and some of their analysis to inform our work and analysis.

Estimation of seasonal discharge (2008–2010) from the formerly perennial Comanche Springs

Chad Norris and Daniel Opdyke
Texas Parks and Wildlife Department

Introduction

The purpose of this analysis was to compile and analyze historical flow data from Comanche Springs and develop a rating curve for springflow measurements.

Historical Springflow Data

Limited historical discharge measurements are available for Comanche Springs prior to the cessation of flow in 1961. Data were obtained from three sources: (1) sporadic daily discharge estimates recorded by Pecos County Water Control and Improvement District No. 1 (Improvement District) from April 1921 through June 1951 and obtained from the Middle Pecos Groundwater Conservation District (Groundwater District); (2) continuous daily data from March 1941 through September 1964 from the U.S. Geological Survey National Water Information System website (http://waterdata.usgs.gov/tx/nwis/sw; gaging station #08444500); and (3) water year average flow data for 1923 to 1961 (Brune 1981).

The sporadic daily data from 1921 to 1951 recorded by the Improvement District and average water year data reported by Brune (1981) are shown in Figure A1. The data show the relative constancy, on a year-to-year basis, of springflows prior to the 1930s, with some decreases evident through the 1930s, and substantial decreases in the late 1940s and early 1950s.

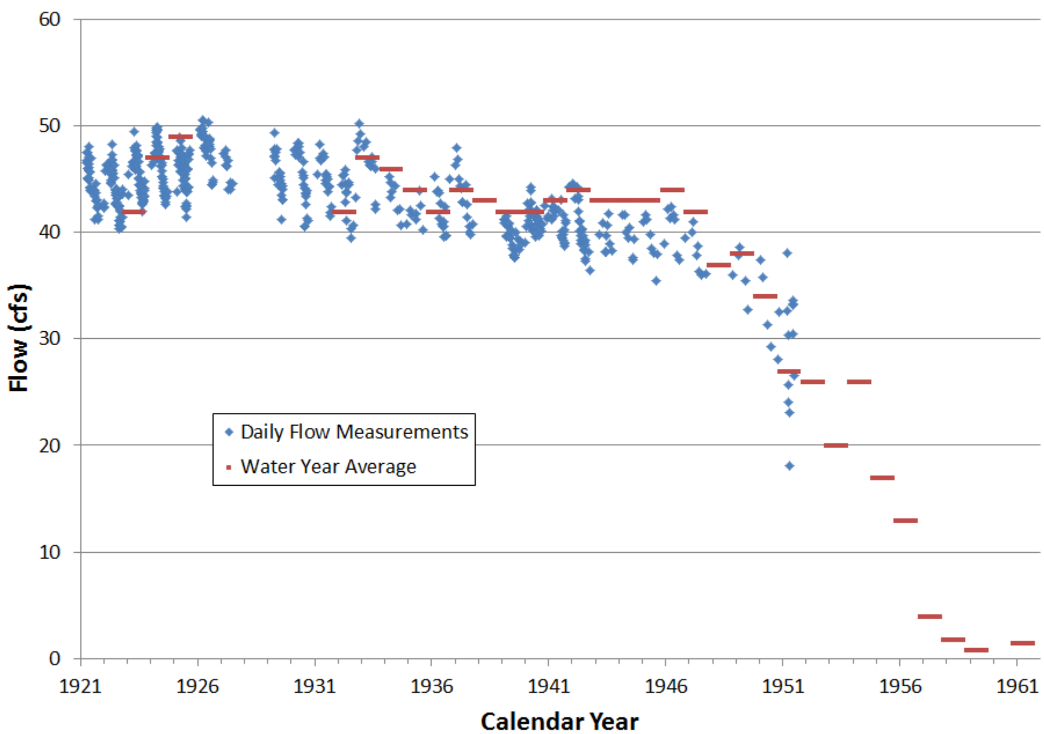

Figure A1: Comanche Springs daily discharge estimates reported by Pecos County Water Control and Improvement District No. 1 and water year data reported by Brune (1981) for the periods of record.

Figure A2 shows the same data for the period 1921 through 1926. This figure suggests that, prior to significant groundwater development, springflows tended to peak around April of each year, reach a minimum around August of each year, and exhibit an annual range of approximately 7 cubic feet per second. These numbers are clearly approximations based on a limited historical dataset, but they do provide context for the behavior of this system prior to significant development.

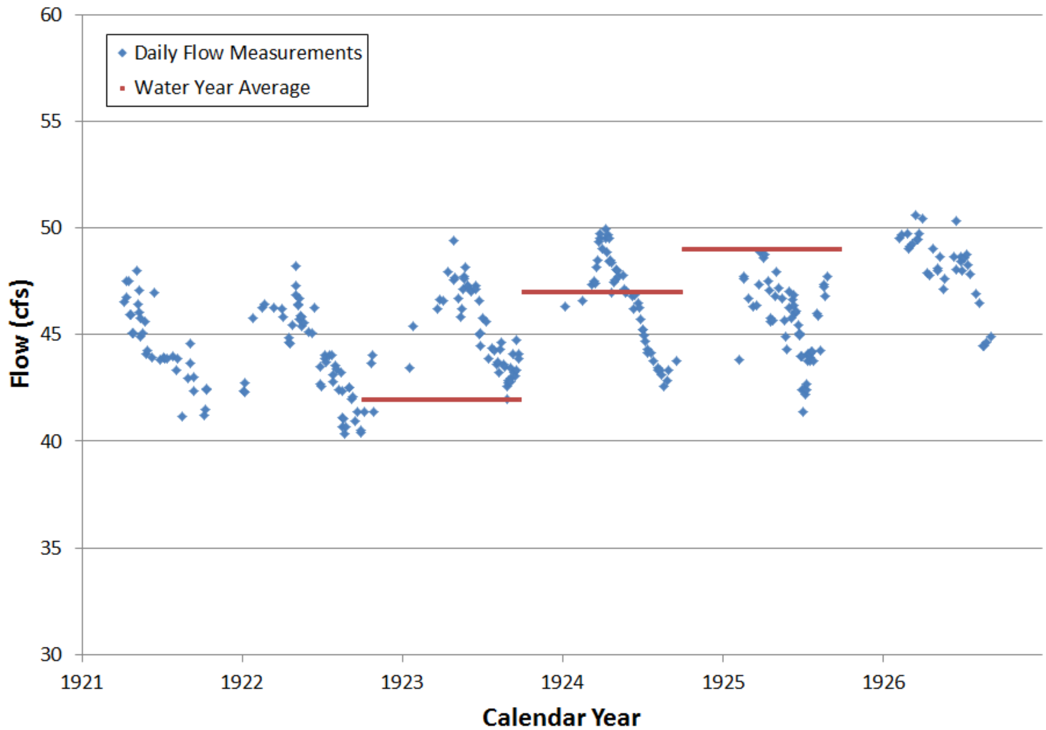

Figure A2: Comanche Springs daily discharge estimates reported by Pecos County Water Control and Improvement District No. 1 and water year data reported by Brune (1981) for the period 1921 through 1926.

The continuous discharge data collected by the U.S. Geological Survey at Comanche Springs from 1941 to 1964 provides more detail on the relatively rapid decline in springflows beginning in the late 1940s (Figure A3; the staircase nature of the flow trace is caused by the data being reported to the nearest integer). Large variations in discharge begin in 1951 and continue through the drought of record (1950s), with flow ceasing for the first time (according to this record) in May 1955. Although springflow returned later in May 1955, the springs only flowed sporadically through the remainder of the year and into early 1956. The springs remained dry throughout the summer and fall of 1956, and springflows did not return until December 4, 1956. A pattern of springflow ceasing in the spring, summer, and fall (that is, the irrigation season) and returning during the winter occurred from 1957 to 1960 before the springs ceased to flow even intermittently in 1961. The U.S. Geological Survey gage recorded zero flow from March 20, 1961 until the gage was terminated on September 30, 1964.

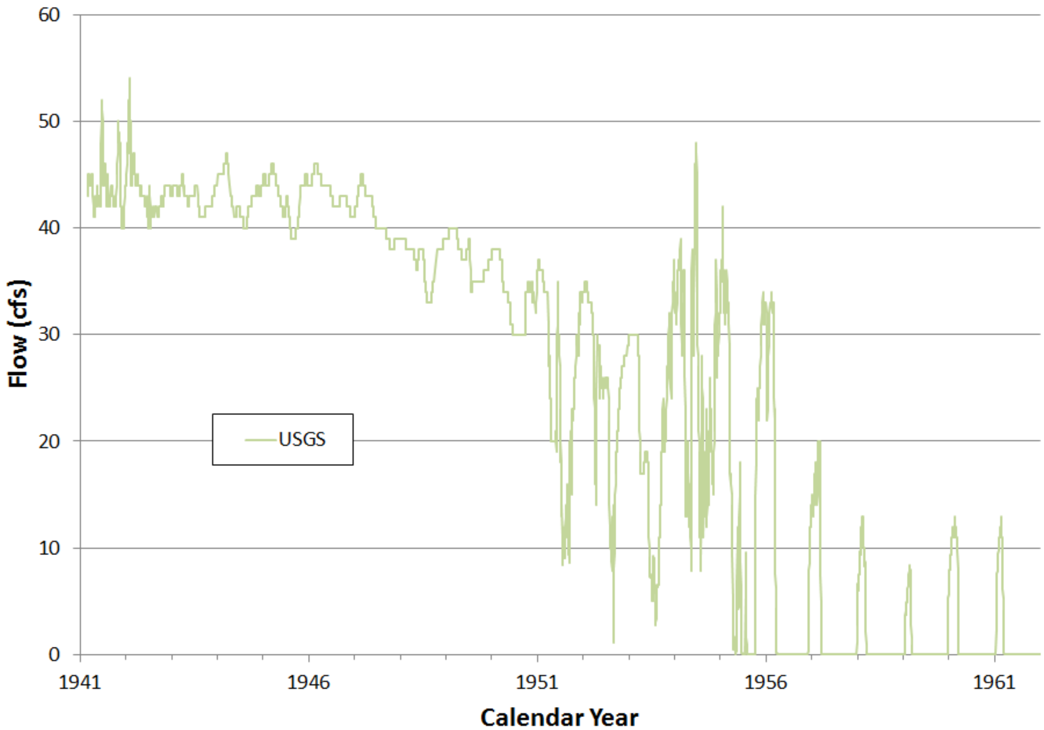

Figure A3: U.S. Geological Survey streamflow data for Comanche Springs at Fort Stockton, Texas, 1941 through 1961 (Station #08444500).

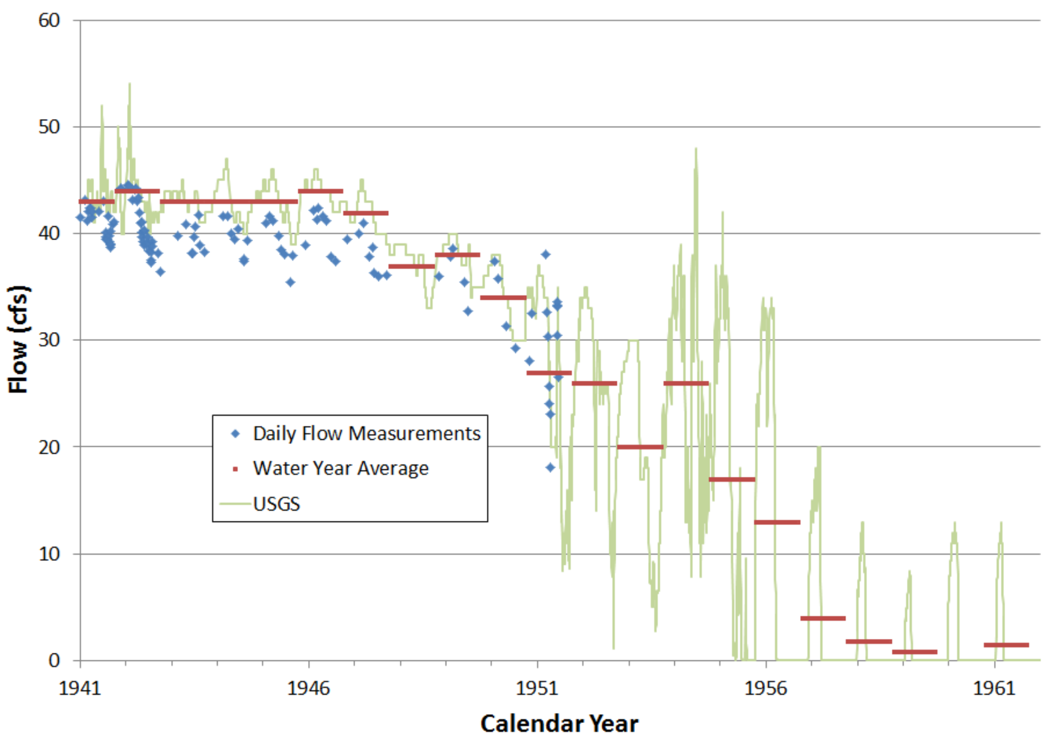

Figure A4: Pecos County Water Control and Improvement District No. 1, Brune (1981), and U.S. Geological Survey streamflow data for Comanche Springs.

To facilitate a comparison of the available data, all of the data from figures A1 and A3 are combined in Figure A4. The U.S. Geological Survey gaging station at Comanche Springs was removed in October 1964 following more than three years of no measurable discharge. To the best of our knowledge, no discharge occurred from Comanche Springs until the winter of 1986 when, after almost 25 years of lying dormant, the springs began to flow intermittently again and have since flowed sporadically during the winter months (Fort Stockton Historical Society 2009). With the exception of a few highly sporadic point measurements, the most recent and thorough attempt to estimate the discharge of Comanche Springs prior to 2008 was made by the Texas A&M AgriLife Extension Service in Fort Stockton in early 1992 (Figure A5). It is unknown when flow began, but the first measurement of 8.8 cubic feet per second was made on January 23, 1992, the highest measurement was just above 14 cubic feet per second (February 27, 1992), and flows ceased around mid-June.

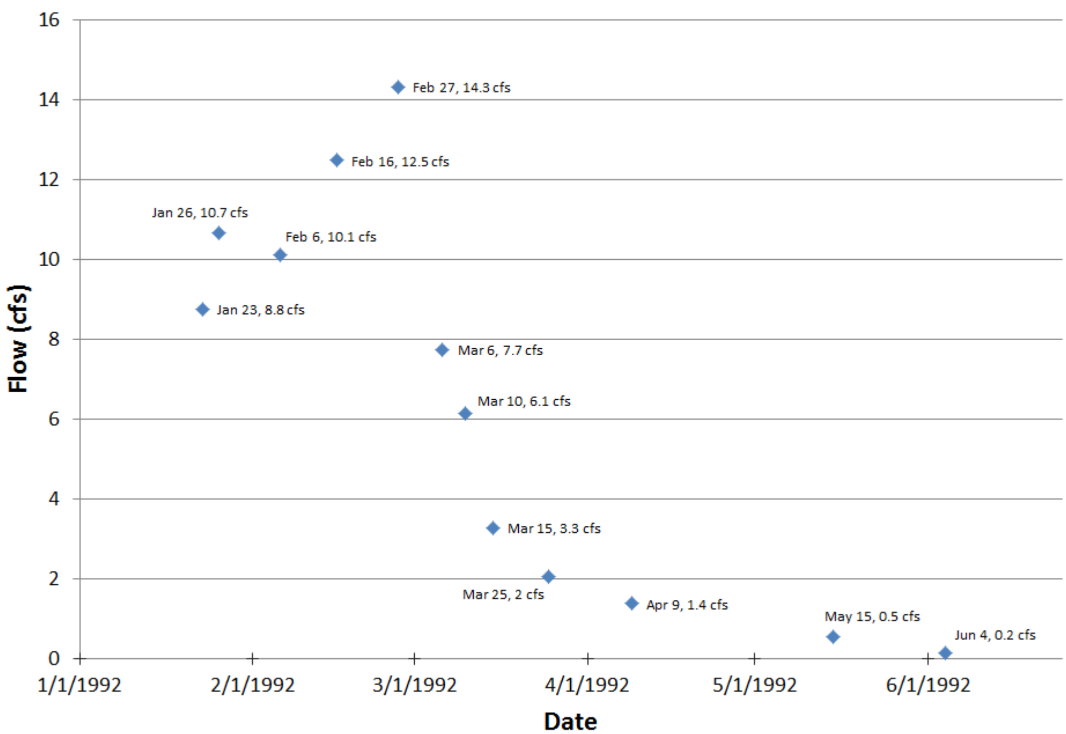

Figure A5: Discharge estimates of Comanche Springs from 1992 (data source, Texas A&M Extension Service, Fort Stockton, Texas).

Variability of Comanche Springs Discharge

The overall decline of Comanche Springs is evident in Figures A1 and A3. Also evident in these figures is an annual variability of springflows. As stated previously, the intra-annual range in springflows for the period 1921 to 1926 is approximately 7 cubic feet per second. Figure A3 also illustrates the intra-annual range in springflows, as measured by the U.S. Geological Survey, and is also about 7 cubic feet per second until the early 1950s. The observed annual variability in spring discharge is the result of fluctuations in precipitation, evaporation, atmospheric temperature, and other weather conditions, but can also be caused by the withdrawal of groundwater.

The variability of a spring may be quantitatively stated as the ratio of its annual fluctuation to its average discharge. This can be expressed by the formula

$$V=100[(a-b)/c]$$

where V is the variability (in percentage)
a is the maximum discharge
b is the minimum discharge, and
c is the average discharge.

Meinzer (1923) defined a constant spring as one having a variability of not more than 25 percent, a subvariable spring as one having a variability of more than 25 but not more than 100 percent, and a variable spring as one having a variability of more than 100 percent. It is important to not confuse variability with reliability (or permanence), which is divided into perennial, intermittent, and ephemeral.

For a reliable estimate of variability, many measurements of flow in different years and seasons are necessary (Meinzer 1923). The aforementioned historical discharge data available for Comanche Springs is sufficient for such an analysis. The 1941 to 1964 U.S. Geological Survey gaging station data were combined with the sporadic data gathered by the Pecos County Water Control and Improvement District No. 1 from 1921 to 1940 to obtain the minimum, maximum, and average discharge for each decade and the variability was calculated (Table A1).

Table A1: Minimum, maximum, and average discharge of Comanche Springs with calculated variability (% and classification) by decade (cfs = cubic feet per second).

Decade	Minimum discharge (cfs)	Maximum discharge (cfs)	Average discharge (cfs)	Variability (%)	Classification (Meinzer, 1923)
1920s	40	51	46	22	Constant
1930s	38	50	43	29	Subvariable
1940s	33	54	42	50	Subvariable
1950s	0	48	16	304	Variable
1960s	0	13	0.8	1688	Variable

The minimum, maximum, and average discharge for Comanche Springs decreased each decade, with the exception of the maximum discharge (which was highest for the 1940s). In contrast, the variability (%) increased each decade from 22 percent in the 1920s to 1,688 percent in the 1960s. According to Meinzer's (1923) classification for variability, Comanche Springs went from being constant (≤ 25 percent) in the 1920s to subvariable (25 to 100 percent) in the 1930s and 1940s and finally variable (> 100 percent) in the 1950s and 1960s. This trend tracks with the increasing use of groundwater in the region.

Methods

Streamflow or discharge is the volume of water passing through a cross section of a stream channel per unit time. For this study, discharge measurements were made according to USGS standard methods as described by Turnipseed and Sauer (2010) using a Sontek Flowtracker Acoustic Doppler Velocimeter ("Flowtracker"). The Flowtracker unit was calibrated prior to the season and data for each discharge estimate were reviewed for quality assurance. Discharge estimates were all made at the same location, which is approximately 40-feet downstream of the iron footbridge that crosses Comanche Creek. This footbridge is approximately 30-feet downstream of a large culvert that focuses springflow from beneath the swimming pool (that is, Big Chief Spring and others that were altered by construction of the swimming pool) and Government Spring. When possible, two discharge measurements were made and then averaged to provide a more accurate estimate. However, time and staff workload issues often limited data collection efforts to only one discharge estimate, with the vast majority being performed by Texas A&M AgriLife Extension Service staff. The manual discharge estimates were used in conjunction with depth measurements from a pressure transducer to establish a rating curve.

To allow for the calculation of daily and total discharges, the water depth (stage) was monitored continuously with pressure transducers that were deployed prior to the beginning of discharges from Comanche Springs. Pressure transducers were deployed in three locations in the winter of 2008–2009 and in two locations in the winter of 2009 to 2010. The In-Situ Level Troll 500 (non-vented) was deployed in Government Spring (both seasons), the Comanche Creek channel downstream of all spring discharges (both seasons), and beneath the City of Fort Stockton swimming pool (2008 to 2009 only). To compensate for atmospheric barometric pressure, an In-Situ Barotroll transducer was also attached to a tree adjacent to the springs. All transducers were set to log stage and temperature data each hour.

Stage data gathered from the transducer deployed in the Comanche Creek channel was used to establish the rating curve and estimate spring discharges. The transducer was deployed in an aluminum housing (constructed by U.S. Geological Staff staff) that was attached to the center of the cement channel with epoxy and screws directly beneath an iron footbridge that crosses the Creek. It is important to note a depth offset that was compensated for, in the event future efforts attempt to reproduce this work. The housing that contained the transducer elevated the unit 0.05 feet (0.6 in) above the bottom of the concrete channel. For example, on February 2, 2010 at 1:00 PM, the measured depth at the transducer was 1.0 feet. At the same time, the transducer reported a water depth of 0.95 feet, exactly 0.05 feet less than the measured water depth of 1.0 feet.

The contribution of historically documented individual springs was estimated on February 4th, 2009. Discharge measurements were made as described above using the Sontek Flowtracker and standard USGS cross-section methods. Because of the modifications made to the spring outflow areas and the main channel of Comanche Creek, it was difficult, if not impossible, to isolate the discharge of each individual spring for direct measurement. As such, the discharge of each spring or group of springs was estimated by measuring discharge within the main Comanche Creek channel upstream and downstream of the spring discharge, with the difference in the discharge measurements providing our estimate. Springs included in this analysis were Big Chief, Government, Blue Hole, Koehler's Store, Church, Jail, and Headwater springs.

Results

Discharge

Manual flow measurements were taken several times in both the 2008–2009 and 2009–2010 winter seasons. The results, plotted against depth, are shown in Figure A6.

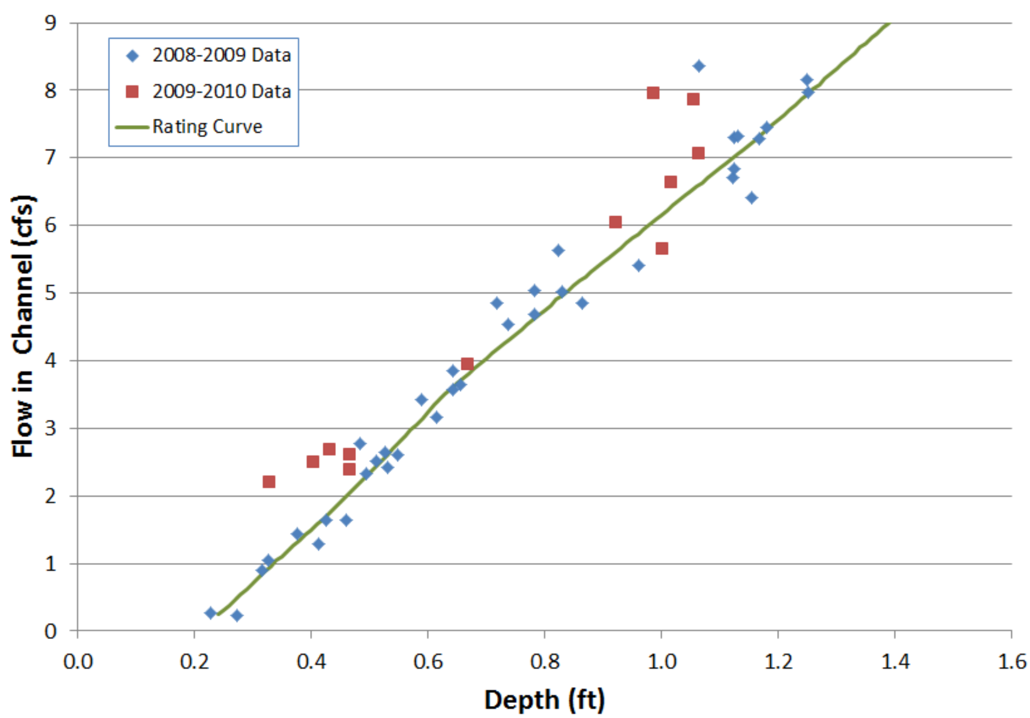

Figure A6: Manual flow and transducer reported depth measurements (cfs = cubic feet per second, ft = feet)

The 2008–2009 data were used by the U.S. Geological Survey to develop a rating curve, which is shown in Figure A6 and reproduced in Attachment A1. Because the 2009–2010 season data were consistent with the 2008–2009 data, the rating curve was not redeveloped using the 2009–2010 data. Such consistency was expected because the channel is concrete.

Using the rating curve, continuous recordings of stage (using the In-Situ Level Troll 500 pressure transducer) can be converted to flow. Figure A7 shows the flow in the channel for the

2008–2009 and 2009–2010 seasons. Figure A7 also includes precipitation data from the Fort Stockton airport. For the 2008–2009 season, there is one significant precipitation event (February 8, 2009) that appears to have generated runoff in the channel. The pressure transducer data were visually inspected to identify the period of likely significant runoff and this transient increase in flow was removed from the flow record for purposes of estimating springflows. In 2009–2010, there were three storm events that appeared to have generated runoff (January 23, January 28, and February 3, 2010). Again, the runoff component was estimated and subtracted from total streamflow to estimate springflow.

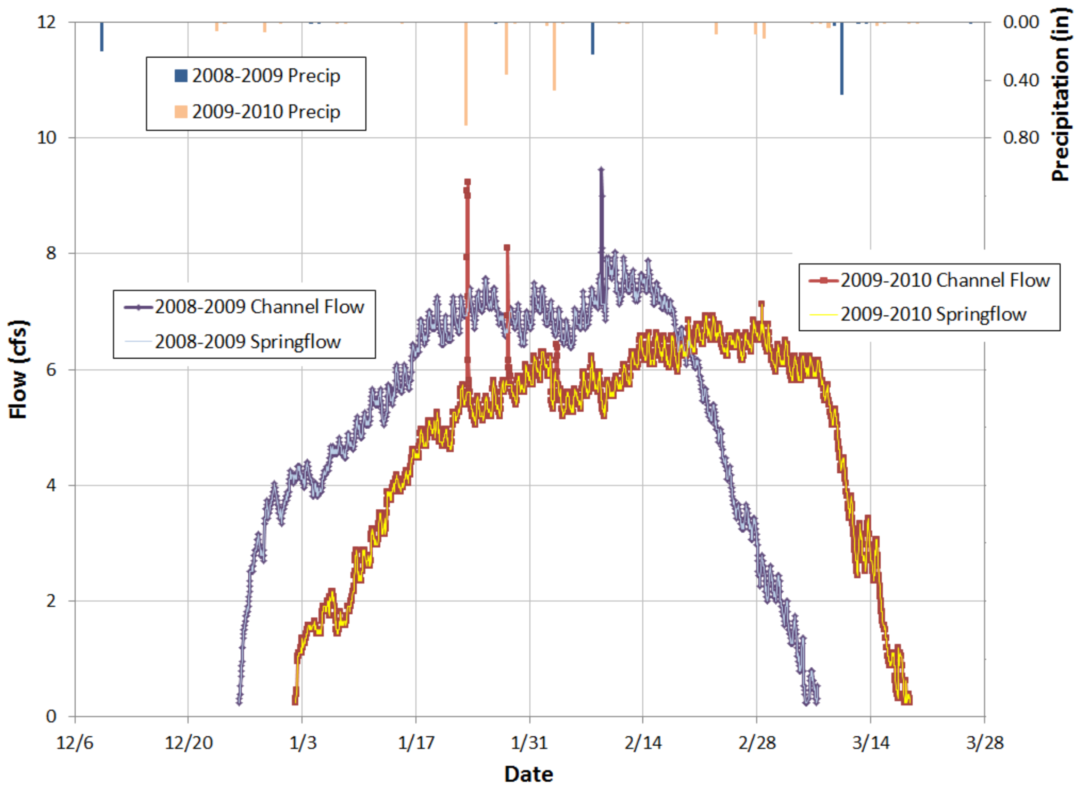

Figure A7: Channel flow, estimated springflow, and precipitation (cfs = cubic feet per second)

For the 2008–2009 season, quantifiable springflow commenced on December 26, 2008, peaked in early February at just under 8 cubic feet per second, and ceased on March 6, 2009. Total estimated springflow for the season was 754 acre-feet over 71 days. For the 2009-2010 season, quantifiable springflow commenced on January 2, 2010, peaked in late February at just over 7 cubic feet per second, and ceased on March 18, 2010. Total estimated springflow for the season was 720 acre-feet over 76 days. Based on this information, the 2009-2010 season started later, ended later, and exhibited about 5 percent less springflow than the 2008–2009 season.

Aquifer Levels

Pressure transducers were also placed within Government Spring (both seasons) and beneath the swimming pool (2008–2009 only) to gain a perspective on the timing of when groundwater arrives and fills the flow system adjacent to the springs. Unfortunately, in both seasons the pressure transducer in Government Spring experienced technical problems. Accordingly, Figure A8 illustrates the data that was collected, but does not have a complete season in either 2008-2009 or 2009-2010.

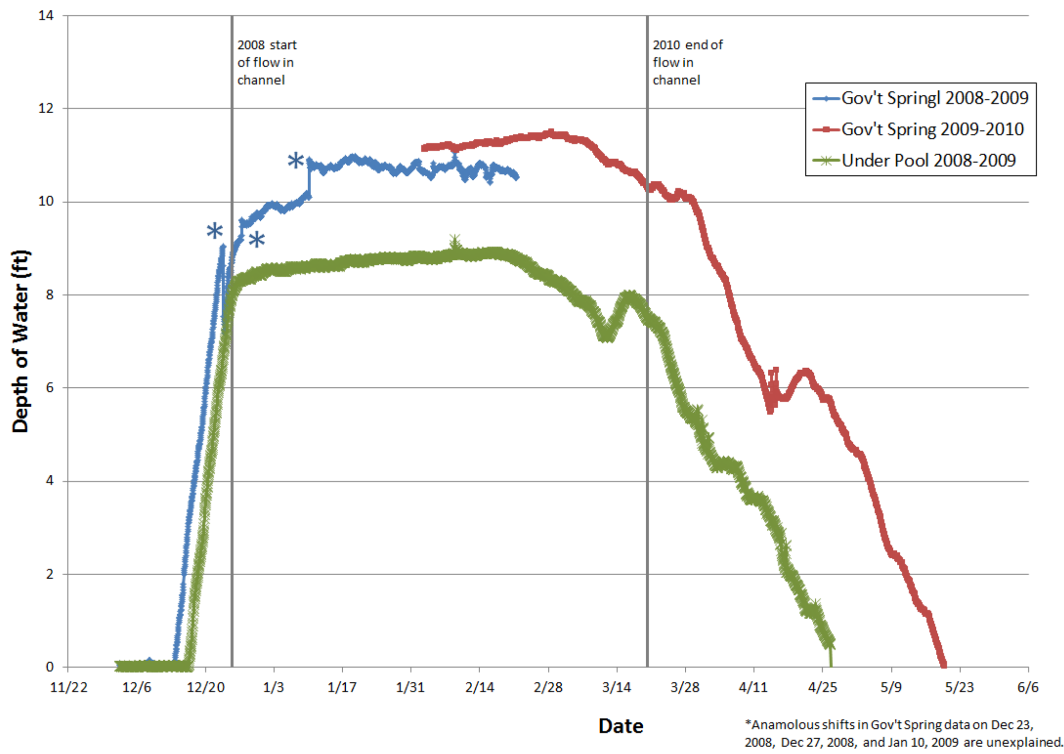

Figure A8: Government Spring and under pool water depth data (ft = feet)

The pressure transducer in Government Spring was not placed at the same absolute elevation as the pressure transducer under the pool, thus the relative depths are not meaningful (based on the proximity of these locations and the fractured nature of the geology, it can be assumed that the water elevations would be nearly identical between these two locations at any given time). However, the slopes of the lines could be used to estimate aquifer properties and behavior.

Diel Fluctuations

Diel fluctuations in aquifer level and springflows are difficult to see in Figure A8 but are more evident in Figure A7. While there is some variation in the data, the average daily range (maximum minus minimum) from January 15 to February 15, 2009 (a period of relatively steady daily average flow) was about 0.6 cubic feet per second. Similarly, the average daily range from February 1 to March 1, 2010 was about 0.5 cubic feet per second.

Springflow Contribution of Individual Springs

The individual spring outlets are displayed geographically in Figure 3.2, and the estimated discharge of each spring or group of springs is summarized in Table A2. According to our measurements, Big Chief and Government springs accounted for 89 percent of the discharge from Comanche Springs, with the remaining 11 percent provided by upstream springs and apparent alluvial seepage entering the channel through cracks in the concrete lining.

No measurable discharge was observed issuing from the most headwater or upgradient springs (that is, Church, Jail, or Headwater springs), although the concrete channel contained small, shallow pools connected by narrow trickles of water. These trickles of water issued from cracks in the concrete channel and not the historic spring orifices of Church, Jail, or Headwater springs as mapped by Brune (1981) and the Fort Stockton Historical Society (2009). A larger volume of water was observed downstream of the Cemetery Road Crossing and upstream of the confluence of Blue Hole Springs, but flow did not extend across the channel and water depth was insufficient (< 1 inch) to measure discharge (Q1). The discharge of Blue Hole Springs (Q2) was measured at 0.23 cubic feet per second (103 gallons per minute), while discharge in the main channel of Comanche Creek (Q3) downstream of the confluence of Blue Hole Spring was measured at 0.59 cubic feet per second (265 gallons per minute). The difference between these two measurements provides an estimated discharge of 0.36 cubic feet per second (162 gallons per minute) from upstream (that is, Church, Jail, or Headwater springs).

Table A2: Measured discharge and discharge estimates for the individual springs from February 4, 2009 (cfs = cubic feet per second, gpm = gallons per minute).

Map location	Measured discharge (cfs)		Spring name	Estimated discharge (cfs)	Estimated discharge (gpm)	Percent (%) of total discharge
Q1	Trickle		**Headwater, Jail, and Church, and unnamed (combined)**	0.36	162	5.04
Q2	0.23		**Blue Hole**	0.23	103	3.22
Q3	0.59		**Koehler's Store**	0.07	31	0.98
Q4	0.66		**unnamed springs**	0.08	36	1.12
Q5	0.74		**Government and Big Chief**	6.4	2,873	89.64
Q6	7.14					

The outflow of Koehler's Spring, which enters the channel from the northeast a short distance (about 30 feet) downstream of the Blue Hole Spring confluence, was also too shallow (< 0.2 feet) to measure discharge. To obtain an estimate of discharge from Koehler's Spring, an additional discharge measurement (Q4) was made in Comanche Creek downstream of their confluence. The difference between this discharge measurement (Q4) and the upstream measurement in Comanche Creek (Q3), provides an estimated discharge for Koehler's Spring of 0.07 cubic feet per second (31 gallons per minute).

The only named springs downstream of Koehler's Spring are Big Chief and Government springs. However, at least three unnamed springs are depicted on historic maps within this reach and the volume of water appeared to be increasing in the intervening reach. An additional discharge estimate was made downstream of the First Street road crossing and upstream of the confluence with Big Chief and Government springs (Q5). The difference between this measurement and the upstream discharge measurement provides an estimated discharge of 0.08 cubic feet per second (36 gallons per minute) for the unnamed springs that enter this reach.

Because the discharge of Government and Big Chief springs is focused into a large culvert that empties into Comanche Creek, it was not possible to isolate the discharge of these individual orifices. To estimate the discharge of these springs as a group, we measured discharge downstream of their confluence with Comanche Creek and obtain the difference between this and the upstream measurement. This provided an estimated combined discharge for Big Chief and Government springs of 6.4 cubic feet per second (2,873 gallons per minute).

The lack of flow from the upgradient springs (Headwater, Jail, and Church) may be the result of insufficient head pressure. In other words, the water elevation in the aquifer is insufficient to produce flow from the higher elevation orifices. Two of the named spring orifices upstream of Cemetery Road were historically described as moderately large springs (average discharge 1 to 10 cubic feet per second). Discharge from these upgradient springs during our investigation was only a small fraction (less than 1 percent) of the reported historic discharge, if flow was present at all.

Brune (1981) mapped a total of 13 spring outlets associated with the Comanche Springs system. Five of the 13 springs mapped by Brune were identified as larger springs (1 to 10 cubic feet per second discharge on average). Given the current seasonal discharge of Comanche Springs, none of the spring orifices would be considered large or even small springs (.01 to 1.0 cubic feet per second).

Temperature Data

An important feature of many springs is the thermal consistency they display through the year (Hynes 1970, Ward 1992, Van Der Kamp 1995). The average water temperature of a typical spring is nearly equal to the average mean annual air temperature in the area (Meinzer 1923, Van Der Kamp 1995). As a result, spring environments in the temperate zone are generally much cooler than other natural surface waters in the summer months and warmer in the winter months. Based on water temperature, Meinzer (1923) divided springs into thermal and non-thermal springs. Thermal springs included hot (average temperature >37º C) and warm (average temperature <37º C) springs. Non-thermal springs were divided into (1) springs whose waters have temperatures approximating the mean annual air temperature in the locality in which they exist and (2) springs whose waters are appreciably colder.

More recently, Springer and others (2008) offered a comprehensive classification of springs, including five classes of springs based on temperature:

1. Cold-water springs: >12.2º C cooler than the mean annual ambient temperature
2. Normal springs: Within 12.2º C of the mean annual ambient temperature
3. Warm springs: >12.2º C warmer than the mean annual ambient temperature, but <37.8º C
4. Hot springs: >37.8º C warmer than the mean annual ambient temperature, but <100º C
5. Superthermal springs: >100º C warmer than the mean annual ambient temperature

Daily air temperature for Fort Stockton and water temperature data for Comanche Springs (as measured by transducer in Government Spring) are presented in Figure A9 for 2008–2009 and in Figure A10 for 2009–2010. Basic statistics (minimum, maximum, and average for the period of measurable flows) are presented in Table A3. Water temperature remained relatively constant, both daily and throughout the season, for both periods, with an average of 22.86º C (standard deviation = 0.32) from 2008–2009 and 22.81º C (standard deviation = 0.31) from 2009–2010. In contrast to water temperature, air temperature displayed daily swings of 30º C or more, which is characteristic of cold, semi-arid climates.

The mean annual ambient temperature for Fort Stockton, Texas is 18º C (NCDC 2005), which is approximately 5° C lower than the average of the sonde measurements reported herein. Based on Meinzer's (1923) classification of springs by temperature, Comanche Springs would be classified as a non-thermal spring whose temperature approximates the mean annual ambient temperature of the area. Based on the classification system offered by Springer and others (2008), Comanche Springs is a normal spring (within 12.2º C of the mean annual ambient temperature).

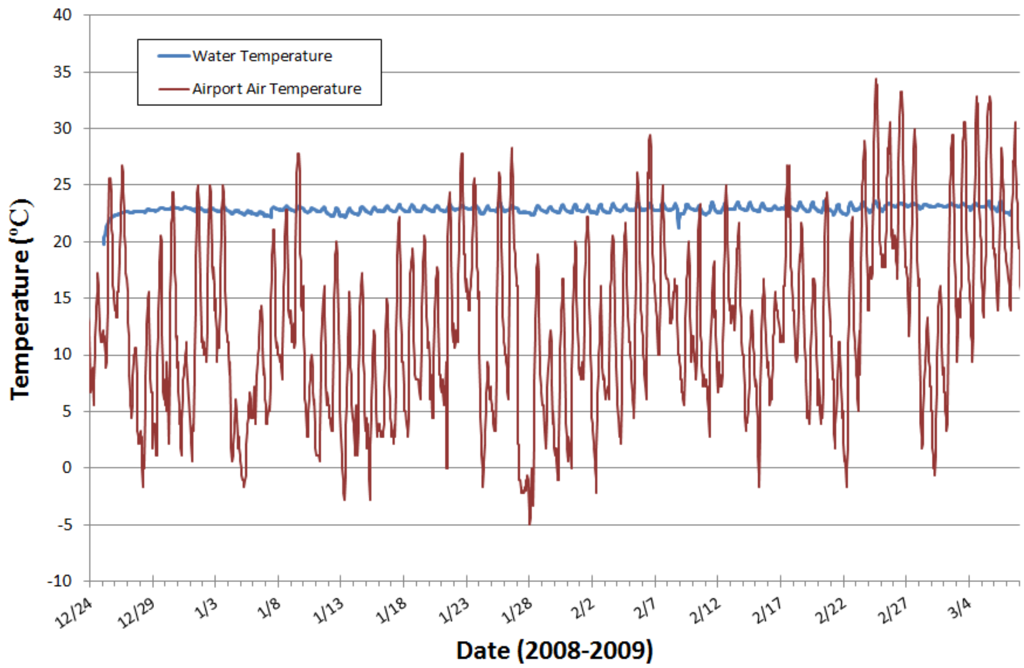

Figure A9: Daily water and air temperature from Comanche Springs for 2008–2009.

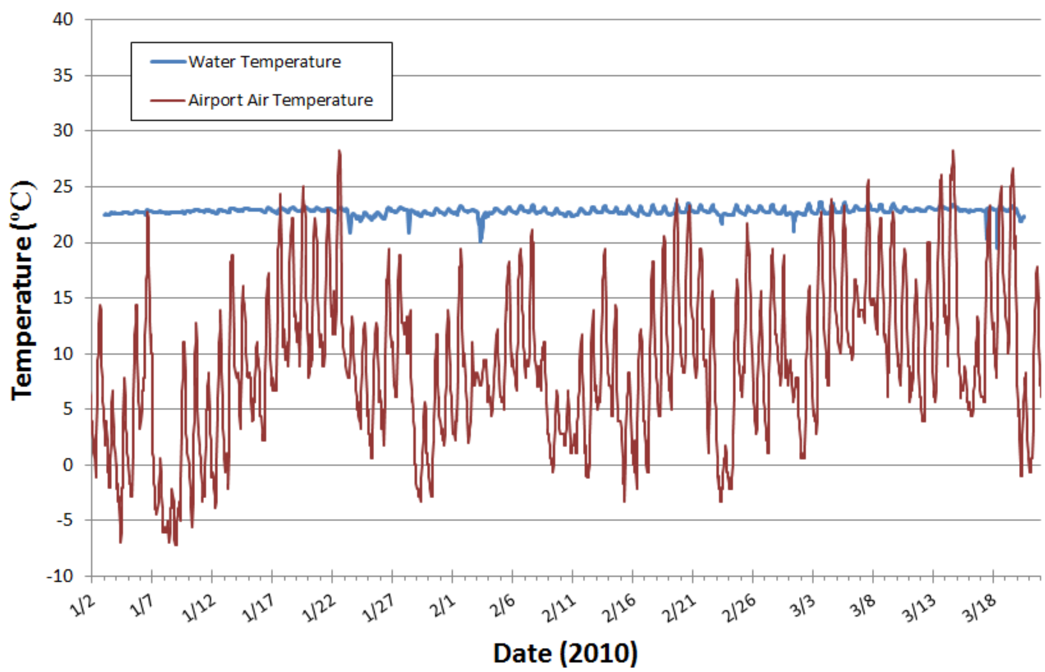

Figure A10: Daily water and air temperature from Comanche Springs for 2009–2010.

Table A3: Statistics for temperature (ºC) data obtained at Comanche Springs.

	2008-2009		2009-2010	
	Water	Air	Water	Air
Minimum	19.8	-5.0	19.5	-7.2
Maximum	23.6	34.4	23.7	28.3
Average	22.9	12.2	22.8	8.7
Std Deviation	0.3	7.9	0.3	7.2

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Attachment A1

Rating Curve

Depth (ft)	Q (cfs)	Depth (ft)	Q (cfs)	Depth (ft)	Q (cfs)	Depth (ft)	Q (cfs)	Depth (ft)	Q (cfs)	Depth (ft)	Q (cfs)
0.24	0.24										
0.25	0.31	0.55	2.79	0.85	5.11	1.15	7.19	1.45	9.46	1.75	11.70
0.26	0.39	0.56	2.88	0.86	5.18	1.16	7.26	1.46	9.54	1.76	11.80
0.27	0.46	0.57	2.97	0.87	5.25	1.17	7.34	1.47	9.61	1.77	11.90
0.28	0.54	0.58	3.06	0.88	5.32	1.18	7.41	1.48	9.69	1.78	11.90
0.29	0.62	0.59	3.15	0.89	5.39	1.19	7.49	1.49	9.76	1.79	12.00
0.30	0.71	0.60	3.24	0.90	5.46	1.20	7.56	1.50	9.84	1.80	12.10
0.31	0.79	0.61	3.34	0.91	5.53	1.21	7.64	1.51	9.92	1.81	12.20
0.32	0.87	0.62	3.43	0.92	5.60	1.22	7.72	1.52	9.99	1.82	12.20
0.33	0.96	0.63	3.52	0.93	5.67	1.23	7.79	1.53	10.10	1.83	12.30
0.34	1.04	0.64	3.59	0.94	5.74	1.24	7.87	1.54	10.10	1.84	12.40
0.35	1.11	0.65	3.67	0.95	5.81	1.25	7.94	1.55	10.20	1.85	12.40
0.36	1.19	0.66	3.74	0.96	5.88	1.26	8.02	1.56	10.30	1.86	12.50
0.37	1.27	0.67	3.81	0.97	5.95	1.27	8.09	1.57	10.40	1.87	12.60
0.38	1.35	0.68	3.89	0.98	6.02	1.28	8.17	1.58	10.40	1.88	12.70
0.39	1.43	0.69	3.96	0.99	6.09	1.29	8.25	1.59	10.50	1.89	12.70
0.40	1.50	0.70	4.03	1.00	6.16	1.30	8.32	1.60	10.60	1.90	12.80
0.41	1.58	0.71	4.11	1.01	6.23	1.31	8.40	1.61	10.70	1.91	12.90
0.42	1.66	0.72	4.18	1.02	6.30	1.32	8.47	1.62	10.80	1.92	12.90
0.43	1.74	0.73	4.25	1.03	6.37	1.33	8.55	1.63	10.80	1.93	13.00
0.44	1.82	0.74	4.32	1.04	6.44	1.34	8.63	1.64	10.90	1.94	13.10
0.45	1.91	0.75	4.39	1.05	6.51	1.35	8.70	1.65	11.00	1.95	13.20
0.46	1.99	0.76	4.47	1.06	6.57	1.36	8.78	1.66	11.10	1.96	13.20
0.47	2.08	0.77	4.54	1.07	6.64	1.37	8.85	1.67	11.10	1.97	13.30
0.48	2.17	0.78	4.61	1.08	6.71	1.38	8.93	1.68	11.20	1.98	13.40
0.49	2.25	0.79	4.68	1.09	6.78	1.39	9.00	1.69	11.30	1.99	13.40
0.50	2.34	0.80	4.75	1.10	6.85	1.40	9.08	1.70	11.40	2.00	13.50
0.51	2.43	0.81	4.82	1.11	6.92	1.41	9.16	1.71	11.40	2.01	13.60
0.52	2.52	0.82	4.90	1.12	6.99	1.42	9.23	1.72	11.50	2.02	13.70
0.53	2.61	0.83	4.97	1.13	7.06	1.43	9.31	1.73	11.60		
0.54	2.70	0.84	5.04	1.14	7.12	1.44	9.38	1.74	11.70		

Appendix B

List of Defendants and Special Defendants in the District Court Case

This list comes from Johnson and Montague (1953) and presents the defendants in the order as listed and as described.

- Defendants (24)
    - Clayton W. Williams
    - T.B. Armentrout
    - E.L. Brown
    - City of Fort Stockton, Texas, a municipal corporation
    - W.R. Cochran
    - Lloyd L. Davis
    - W.H. Dullnig, Federal Land Bank of Houston, Texas, a corporation
    - M.R. Gonzales
    - Luther C. Holladay
    - A.J. Keith, Leon Land & Cattle Company, a corporation
    - Mutual Life Insurance Company of New York, a corporation
    - National Life & Accident Insurance Company, Inc., of Nashville, Tennessee, a corporation
    - H.M. Newnham
    - Dow Puckett
    - Thurman Simmons
    - M.C. Slaten
    - William Slaten, a minor
    - L.A. Taliaferro
    - C.G. Teitsch
    - Viola Dullnig Teitsch Howard
    - D.R. Whittenburg
    - H.S. Whittenburg
    - J.C. Williams
    - W.J. York

- Special Defendants (61)
  - Othro W. Adams
  - B.B. Armstrong
  - Clara H. Armstrong, a single woman
  - Gayle Armstrong, a single woman
  - G.B. Armstrong, Jr.
  - Iva A. Armstrong, a single woman
  - Jack B. Armstrong
  - Murphy S. Armstrong
  - Wenzel Armstrong
  - B.L. Blackburn
  - Joe Boswell
  - Ray V. Carter
  - E.R. Claver
  - J.M. Childers
  - G.H. Crone
  - Paul Crone
  - J.C. Cunningham
  - Niarvin Dees
  - E.R. Dyche
  - J.H. Dyche
  - M.E. Fincher
  - Lester Griffith
  - F.A. Guthrie
  - Lester D. Guthrie
  - E.M. Hahn
  - Laura Sue Hall, a single woman
  - Max Hall
  - Loren G. Hillger
  - T.W. Hillin
  - William Hoefs
  - Mrs. Ida Johnson, a single woman
  - Roy Lannom
  - Burney Ligon
  - J. Burney Ligon
  - H.W. Lester
  - B.E. Mitchell
  - N.M. Mitchell
  - B.L. Moody
  - Tom G. Moore
  - C.E. McIntyre
  - J.G. Nevans
  - Edward C. Niemann

- Special Defendants continued
    - J.S. Oates
    - Cecil Patterson
    - Jerry Puckett
    - M.C. Puckett
    - J.B. Ratliff
    - Sim A. Reeves
    - Coke R. Rhodes
    - Tom B. Rhodes
    - Ernest Riggs
    - E.A. Robertson
    - L.R. Simon
    - Bishop G. Smith
    - G.E. Spinnler
    - Charles Stone
    - Paul Teas, Jr.
    - West Texas Utilities Company, a corporation
    - Lee O. White
    - Clyde Wilson
    - H.A. Wyche

Appendix C

Flow Measurements Taken at Comanche Springs During this Study

Table C1

Measurement date	Flow (cubic feet per day)
3/19/2018	~5

Table C2

Measurement date	Flow (cubic feet per day)	Notes
12/30/2019	7.94	
1/7/2020	10.10	
1/13/2020	9.23	
1/20/2020	9.84	
1/27/2020	10.10	pool draining
1/29/2020	9.84	
2/3/2020	9.84	
2/10/2020	9.84	
2/17/2020	9.84	
2/21/2020	10.40	
2/24/2020	10.80	
3/2/2020	8.55	
3/4/2020	11.10	rain
3/9/2020	8.55	
3/16/2020	7.64	
3/23/2020	7.34	
4/14/2020	5.88	
4/27/2020	4.68	

Appendix D

Natural Pool Morphology

WJE

Wiss, Janney, Elstner Associates, Inc.
6363 North State Highway 161, Suite 550, Irving, Texas 75038
972.550.7777 tel
Texas Registered Engineering Firm F-0093
www.wje.com

December 31, 2019

Sharlene Leurig
Chief Executive Officer
Texas Water Trade
801 Barton Springs Road
Austin, Texas 78704

Comanche Springs Swimming Pool
Preliminary Pool Basin Volume Estimate
WJE No. 2019.6992.0

Dear Ms. Leurig

In accordance with the agreement dated October 16, 2019, between Texas Water Trade and Wiss, Janney, Elstner Associates, Inc. (WJE), WJE has completed initial development of a volume model and an estimate of the volume of the pool basin.

Background

The existing Comanche Springs swimming pool located in Fort Stockton, Texas is at or near the site of a prehistoric spring-fed basin that was surrounded by wetlands. Comanche Springs is a set of artesian springs fed from deeper caverns and fissures in the underlying limestone of the Trinity-Edwards Aquifer. Historical records indicate that the springs flowed continuously through the 1940s, intermittently until the 1960s, and infrequently since then. The cessation of flow has been linked to an increase in extraction of water from the aquifer for municipal, agricultural, and industrial uses.

The original pavilion and areas surrounding the pool were developed, along with improvements to the natural basin, by the Civilian Conservation Corps in the 1930s. The existing reinforced concrete pool structure and surrounding deck were constructed in 1953. Repairs to the pool and pool deck were completed in the 1980s, early 2000s, and in 2017.

Since the late 1980s, intermittent spring flow typically starts near the end of each calendar year and continues until late spring. The timing and flow volume are a function of precipitation within the aquifer recharge zone and the amount of water extracted.

It is our understanding that Texas Water Trade is working with Middle Pecos Groundwater Conservation District and other local water districts, the City of Fort Stockton, and Pecos County to determine the feasibility of restoring year-round spring flow to Comanche Springs. One potential goal of this effort may the restoration of the Comanche Springs swimming pool to a configuration similar to the pre-1953 natural basin pool or another spring-fed pool configuration.

During 2016 and 2017, WJE was retained by Pecos County to investigate distress in a portion of the pool deck and the design repairs to remedy to that distress.

Document Review

WJE reviewed the "Survey/Audit Report" by Aquatic Facilities Assessment, dated January 7, 2002. Portions of this report describe the pool construction and condition in 2002. Earlier information related to a 1983 assessment and subsequent repairs designed by Charles F. Terry, Inc. consulting engineers was included in this report. The report also includes a summary that describes an investigation by hydrogeologist Albert E. Ogden with Central Texas Geological Services. The summary is not dated but is accompanied by a mail transmittal from Charles F. Terry, Inc. to Pecos County dated April 28, 1983.

The repairs detailed by Charles F. Terry, Inc. included injection of cracks in the concrete pool shell and gunite repairs to the piers supporting the pool. One repair to the northeast pool deck detailed in the 1983 package was not completed at that time and was the subject of the repairs designed by WJE in 2017.

Separately, WJE researched public information regarding the pre-1953 pool to understand how the 1953 construction may have altered the basin.

Field Investigation

On November 8, 2019, WJE personnel visited the pool site to gather information to be used in our assessment. At that time, it was discovered that portions of the area under the pool were not safely accessible. Wet and muddy conditions did not allow full documentation to be made at that time. Photographs were captured in accessible areas as a means of documenting the structure and basin. These photographs were to be used in developing a volumetric model of the under-pool basin. The figures attached to this letter are examples of these photographs.

Model development

Using measurements and photographs from 2017 and 2019, WJE developed a computer model of the pool basin using Vectorworks computer aided design software. This model estimates the gross pool volume to be 454,000 gallons. This volume is consistent with the gross capacity of 450,000 gallons stated in the 2002 Aquatic Facilities Assessment report. The depth and shape of the bedrock basin below the pool is unclear due to the presence of an unknown depth of soil and the irregular soil surface. Our model uses approximations of the visible surfaces. (The 1983 hydrogeology summary reports a soil depth of one foot or less across the basin. It is not clear how the return of annual flow may have altered this condition.)

The 1983 hydrogeologist's report also describes three fissures under the pool. WJE did not observe these fissures in the soil-covered area under the pool but did observe that the soil under the swimming pool does have a series of low areas that could indicate the locations of fissures (As might occur if soil is carried down into the fissures as water drains into them). One fissure is visible uphill of the pool, inside the cast-in-place culvert box between the swimming pool and the spring-fed wading pool. On the slope down from this fissure, a rough concrete slab/riprap overlies the likely location of a fissure, below an outfall from the concrete culvert box. Under the deck along the northwest side of the pool, the limestone bedrock is visible on the upward-sloping surface along the edge of the basin. There is an approximately five-foot tall retaining wall extending from basin floor to the concrete pool deck along this side of the basin. Portions of this wall are cast-in-place concrete, portions are stone masonry, and one segment is hardened, stacked bags of concrete that appear to have been installed to support the deck and retain the soil. A portion of the remaining stone masonry wall near the box culvert has tumbled down, exposing the soil and rock behind it.

A stone masonry retaining wall lines the short, southwest end of the basin, from the Big Chief spring to the south corner. At this corner, the masonry wall joins a cast-in-place concrete retaining wall that extends parallel to the long, southeast side of the concrete pool to the east corner of the pool.

The short northeast end of the pool has a concrete tunnel measuring approximately five feet wide and five feet deep against the pool shell. This tunnel was constructed in 2018 to reduce erosion along this end of the pool and is surrounded by soil and/or concrete fill.

Based on the current data, we expect that the model represents the configuration of the basin within about plus-or-minus twenty percent of the actual volume. The nominal volume computed from the model is 1.2 million gallons (164,000 cubic feet). Based on this estimated volume and variation, the basin volume is estimated to be between 1.0 million and 1.5 million gallons. As soon as the basin can be safely entered during 2020, WJE plans to take additional measurements and refine the model to increase the accuracy of our volume estimate.

Conclusions

Based on the available data from 2017 and 2019, along with information from other sources, WJE has estimated the existing basin. The volume bounded by the existing retaining wall edges and soil/rock floor, is estimated to be between 1.0 million gallons and 1.5 million gallons. This figure was derived from a model that should be considered a starting point for refinement.

The electronic model will be provided under separate covers.

Thank you for the opportunity to provide this service to Texas Water Trade. If there are questions regarding our estimate, the model, or other aspects of this project, please contact me at your convenience.

Sincerely,

WISS, JANNEY, ELSTNER ASSOCIATES, INC.

STATE OF TEXAS
JOHN B. TURNER
98646
LICENSED
PROFESSIONAL ENGINEER
31 December 2019

John B. Turner, CSP, PE
Senior Associate and Project Manager

FIGURES

Figure 1. Looking northeast from the west/southwest side of the pool. The retaining wall is directly below the deck at the camera position.

Figure 2. Looking south from the west/southwest side of the pool (same location as previous image). Big Chief spring is in the caged area (in the dashed oval).

Figure 3. Under the east (southeast) side of the pool deck, looking back toward the entry at the east corner. The light source at the upper cwner is the tunnel across the northeast end of the pool.

Figure 4. Looking down the southeast side of the pool, from the east corner toward the south corner. Concrete retaining wall on the left; pool structure on the right.

Figure 5. Under the pool deck, looking south toward the south corner. Concrete retaining wall on the left; stone masonry retaining wall ahead, center; pool structure on the right.

Figure 6. Looking west from the south corner. Stone masonry retaining wall on the left and ahead; pool structure on the right.

Figure 7. Looking northwest under the mid-section of the pool. The water-filled depression may correspond to a fissure in the rock basin.

Figure 8. Looking northwest under the pool. The concrete and riprap at the outfall of the box culvert on the west side are visible in the distance.

Figure 9. Looking from the southeast side near mid-pool toward the deep end. An unknown PVC pipe is visible in the distance.

Figure 10. Inside the box culvert on the west side, looking south. The pipe ahead connects to the main spring (Big Chief spring). The opening to the pool basin is on the left. A fissure in the rock is near the bottom of the ladder. Below the pipe ahead, soil is washed out below the pipe and to the left of this is an area of collapsed stone masonry wall (not visible).

Figure 11. Below the west/northwest side pool deck, looking southwest from the entry point at the box culvert. The pool structure is on the left; rubble of the collapsed stone masonry wall is visible ahead; The retaining wall at the edge of the basin is on the right.

Figure 12. Same collapsed wall segment as in previous figure, looking opposite direction (northeast). Intact stone masonry wall is on the left with the undermined base visible.

Figure 13. Wall repair using bagged materials.

Figure 14. Retained area on west side of basin. The location of the collapsed wall is on the left. The open fissure into the concrete box is on the lower right.

Figure 15. Looking east from the entry point/outfall from the box culvert. This is the area in Figure 8, viewed from the opposite direction.

Figure 16. Looking southeast toward the Big Chief spring. Pool structure is on the left; collapsed stone masonry wall in the foreground; retained west side of the basin is on the right. Ahead in the distance, a large diameter concrete pipe is visible to the left of the columns; Big Chief spring is to the right of this.

Appendix E

Springflow Deficit Approach for Estimating Pumping

When we discovered that the springflow and pumping water budgets for the aquifer for 1920, 1958, and 2012–2016 all resulted in about 49,000 acre-feet per year, we realized that this same approach could be used to estimate the amount of pumping in the aquifer when we had measurements of springflow.

The pre-pumping water budget for the springshed in the Edwards-Trinity Aquifer for Comanche Springs is

Equation (1) $$Q_r + Q_{cf} = \bar{Q}_{ls} + \bar{Q}_{cs} + Q_{out}$$

where

Q_r = recharge to the Edward-Trinity Aquifer for the Leon-Belding Irrigation Area
Q_{cf} = cross-formational flow into the Leon-Belding Irrigation Area
$\bar{Q}_{ls}$ = long-term average of pre-pumping discharge from Leon Springs and its flow-enhancing wells
$\bar{Q}_{cs}$ = long-term average of pre-pumping but post-flow-enhancing wells at Leon Springs discharge from Comanche Springs
Q_{out} = flow out of the springshed through the Edwards-Trinity Aquifer

By springshed, we mean the area that defines the primary flow system in the Edwards-Trinity Aquifer to Comanche and Leon springs. Note that many researchers incorrectly use the term "recharge" to refer to all inflow into a flow system. For example, many researchers include cross-formational flow as part of recharge. However, recharge only refers to water that infiltrates to the water table of an aquifer.

If we assume that Q_{out} is much smaller than spring flow, something that's supported by lower permeabilities seen just outside the Leon-Belding Irrigation Area as well as with consistent water budgets under different production scenarios, we arrive at

Equation (2) $$Q_r + Q_{cf} = \bar{Q}_{ls} + \bar{Q}_{cs}$$

Which says that the combined flows at Leon and Comanche springs represent the total inflow into the Leon-Belding Irrigation Area. Harden and others (2011) used similar logic when assigning initial values of recharge to their model except that they did not include cross-formational flow.

Spring flows between 1920 and 1940, when there wasn't much if any well drilling in the Leon-Belding Area, were stable, suggesting a consistent source of recharge and cross-formational flow, which follows that $\bar{Q}_{ls} + \bar{Q}_{cs}$ can be treated as a constant and can be used to approximate $Q_r + Q_{cf}$. Once there is pumping, Q_r and Q_{cf} could increase in response to that pumping. Given that there is no rejected recharge in the pre-development recharge zone for the springshed, it is unlikely that Q_r would increase; however, pumping in the Leon-Belding Irrigation Area could capture flow from a larger recharge area and thus increase Q_r. Cross-formational flow, Q_{cf}, could increase due to a lower hydraulic head in the Edwards-Trinity Aquifer thus increasing the upward potential for flow. Because we didn't see a change in the water budget for pre- and post-pumping periods, we will assume that increases in recharge and cross-formational flow are small relative to spring flows.

Substituting $\bar{Q}_{ls} + \bar{Q}_{cs}$ for $Q_r + Q_{cf}$ and including pumping and irrigation return flow results in

Equation (3) $$\bar{Q}_{ls} + \bar{Q}_{cs} + Q_{rf} = Q_{ls} + Q_{cs} + Q_p$$

where

Q_{rf} = irrigation return flow
Q_{ls} = post-pumping flow at Leon Springs
Q_{cs} = post-pumping flow at Comanche Springs
Q_p = pumping

rearranging the terms and assuming that Q_{rf} is small compared to pumping results in

Equation (4) $$Q_p = (\bar{Q}_{ls} - Q_{ls}) + (\bar{Q}_{cs} - Q_{cs})$$

which is simply that pumping is equal to the decline in springflow at Leon and Comanche springs. When all of the springflow is captured, it means that pumping is greater than the sum of the long-term averages of flow at Comanche Springs and Leon Springs and its flow-enhancing wells.


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