Section 6 (Texas Traditional) Report Review

Attachment to letter dated MAY 3 1 2005

Project Title: Diminished Spring Flows in the San Solomon Spring System, Trans-Pecos, Texas

Final or Interim Report? Final

Job #: WER **Grant #:** E-19

Reviewer Station: Austin ESFO

Lead station was contacted and concurs with the following comments:
☐ Yes ☐ No ☒ Not applicable (reviewer is from lead station)

Interim Report (check one):	**Final Report** (check one):
☐ is acceptable as is	☒ is acceptable as is
☐ is acceptable as is, but comments below need to be addressed in the next report	☐ is acceptable, but needs minor revision (see comments below)
☐ needs revision (see comments below)	☐ needs major revision (see comments below)

Comments:

None.

TEXAS PARKS & WILDLIFE

5/9/2005

FA-TEXAS

GRANT: E-19

Joyce Johnson, Chief
Division of Federal Aid, Region II
U.S. Fish and Wildlife Service
P.O. Box 1306
Albuquerque, New Mexico 87103

Attention: Debra Jones

Dear Joyce:

Finally, we have received and are sending a resubmitted Final Report to the above grant (Diminished Spring Flows in the San Solomon Spring System, Trans-Pecos, Texas). This version is in response to March 15, 2004 comments from the local State Ecological Service Office. If you any questions, please call me at 512-389-4641.

Sincerely,

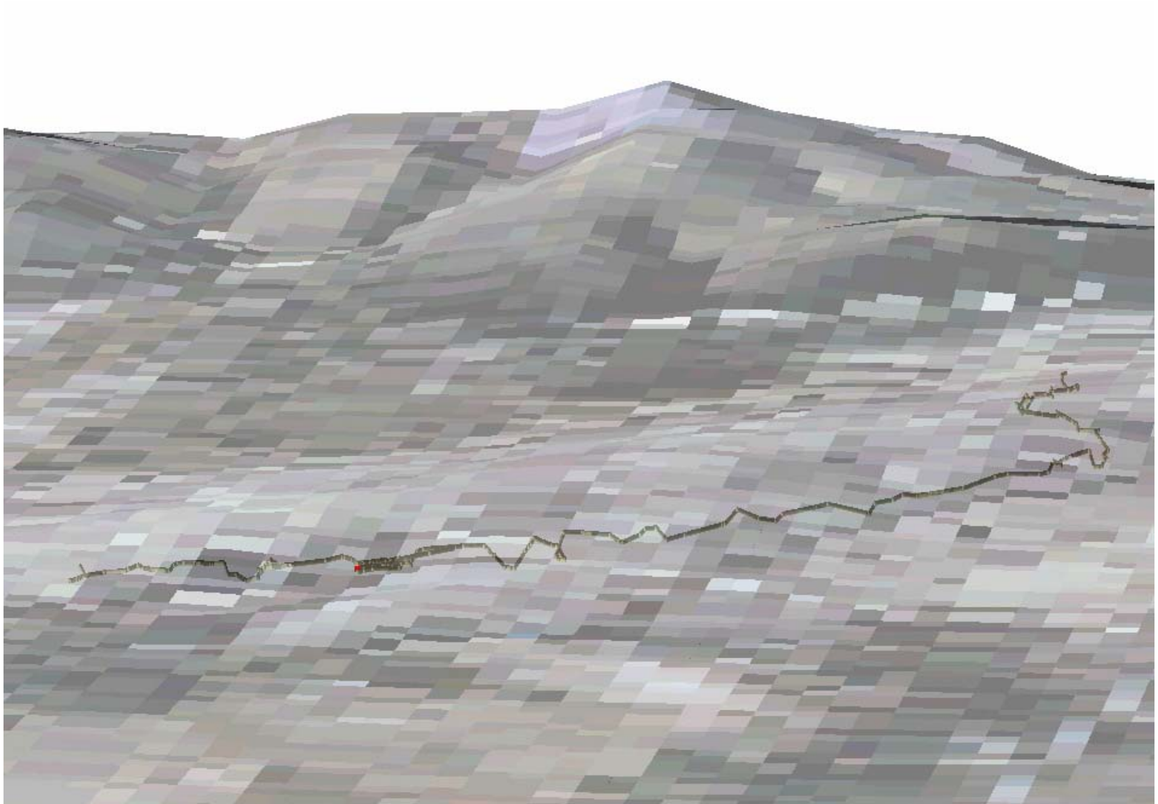
Neil (Nick) E. Carter
Federal Aid Coordinator

NEC

Enclosure

cc: Craig Farquhar
Christina Williams

DIMINISHED SPRING FLOWS IN THE SAN SOLOMON SPRINGS SYSTEM, TRANS-PECOS, TEXAS



MAY 2005

EXECUTIVE SUMMARY

The San Solomon Springs System near Balmorhea, Texas, is comprised of San Solomon, Giffin, Saragosa, Phantom Lake, East Sandia, and West Sandia springs. Spring flow at Phantom Lake Spring has declined from more than 10 cubic feet per second during the 1930s and 1940s to no-flow since 2001. Spring flow at San Solomon Springs, Giffin Spring, and East Sandia Springs has not declined to the same degree as Phantom Lake did during this time. However, Saragosa and West Sandia springs have ceased to flow. Because the San Solomon Springs System supports endangered and threatened fish species, local agriculture, and a State park, there is considerable interest in identifying the source of water to the spring system and the effects of pumping on spring flow.

The primary objectives of this three-year study were to (1) assess the hydrogeology of the source aquifers for the San Solomon Springs System and (2) evaluate the effect, if any, of groundwater pumping on spring flow. To do this, we:

- researched previous studies associated with the study area;
- assessed the geochemistry, including stable and radiogenic isotopes, of the springs and area wells;
- measured water levels and developed maps of water-level elevations and identified potential flow paths to the springs;
- conducted aquifer tests to explore the hydraulic properties of the flow system;
- evaluated historical pumpage and well data for stratigraphic correlations and possible impacts to discharge patterns at the springs;
- examined well logs to assess the geological structure and faults which may influence flow paths;
- compared rainfall events to spring discharge; and
- analyzed previous stream gain-loss studies for assessing levels of surface water and groundwater interaction.

According to previous studies, the San Solomon Springs System is fed by two groundwater flow systems: a local flow system and a regional flow system (White and others, 1941; LaFave and Sharp, 1987; Schuster, 1996; and Sharp and others, 1999). The local flow system is from the Davis Mountains to the south of the springs and is the cause of the spikes in spring flows when the location and intensity of local rainfall are appropriate. The local flow system responds quickly to precipitation and climate. The regional flow system provides the base flow to the springs through groundwater that flows through the Apache Mountains to the west. The regional flow system responds slowly to precipitation and climate. Isotopic analysis suggests that the base flow that feeds the springs is more than 10,000 years old. One of the primary questions of the San Solomon Springs System is - Where does this regional base flow come from?

A number of authors (LaFave and Sharp, 1987; Schuster, 1996; Sharp and others, 1999; Sharp, 2001; and Uliana and Sharp, 2001) suggest that the source of the water flowing through the Apache Mountains to the San Solomon Springs System is from the West Texas Bolson aquifer beneath Wild Horse Flats. This hypothesis was supported by chemical and isotopic compositions, water levels (Nielson and Sharp, 1985), and PHREEQE geochemical modeling. However, our analysis of chemical and isotopic composition of spring water and groundwater suggests that the more likely source of water for the regional base flow is from further north in an area west of the Delaware Mountains. We also believe that some of the water in the springs may also be derived from the Apache Mountains area. Our analysis differs from previous authors in that we used different isotopes (Carbon-14, Carbon-13, and Sulfur-34) over a much larger area and used NETPATH, a geochemical modeling code that simulates geochemical reactions and radiocarbon dating along a flow path. We also age dated the springs and potential source waters.

Because of the uncertainties in delineation of the regional flow system, it is difficult to assess why spring flow in Phantom Lake Spring has declined. Ashworth and others (1997) concluded that flow declines in Phantom Lake Spring and San Solomon Springs was the result of diminished recharge due to an extended dry period rather than from groundwater pumpage. While recent drought has likely had an effect on spring flow, it does not explain the long-term decline of spring flow in Phantom Lake Spring since at least the early 1950s and possibly earlier. Sharp (2001) suggested regional groundwater pumping may be a cause of spring flow declines in the Toyah Basin area. Interestingly, flow in Phantom Lake Spring appears to start declining in the 1950s – around the same time groundwater usage across the state increased considerably in response to drought. However, if the regional flow system is not connected to the West Texas Bolson aquifer beneath Wild Horse Flats, it becomes difficult to correlate spring flow decline to pumping. Additional work is needed to better understand the flow system in and around the Apache Mountains to the west and northwest of the springs before a conclusion is made on the effects of pumping on spring flow. The 6.0 magnitude earthquake on August 16, 1931 near Valentine, Texas may have altered or allowed cementation of historical flow paths. Insufficient historical data limits the correlation between earthquake activity and diminishing spring flows. Ashworth and others (1997) noted that improper placement of new wells could have a detrimental effect on the springs. We agree with this conclusion. Because of the regional scale of the base flow, slow travel time, and the age of the waters issuing from the spring system, we expect that any substantial pumping on the regional flow system will cause a decline in spring flow in the San Solomon Springs system.

We recommend additional work to better understand the San Solomon Springs System and its source waters. While considerable effort was applied during the three-year study to further delineate the extent of the source waters, isotope analyses are relatively expensive and therefore only a limited number of sites could be sampled. Therefore, we recommend:

- additional sampling for isotopes in the Capitan Reef aquifer, both in Texas and New Mexico, around the Delaware Mountains, and in the West Texas Bolson aquifer beneath Wild Horse Flats;
- analyses of isotopic and chemical compositions of rain water in the study area;
- a detailed re-evaluation of historical water-level information in the West Texas Bolson aquifers;
- continued monitoring of the springs and aquifers, particularly under non-drought conditions; and
- more research of the geologic structure in Culberson and Jeff Davis counties.

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STATE OF TEXAS

GRANT NUMBER: WER69

STUDY NUMBER: 84312

TITLE:

DIMINISHED SPRING FLOWS IN THE SAN SOLOMON SPRINGS SYSTEM, TRANS-PECOS, TEXAS

RESEARCH PERIOD: November 16, 2000 to August 31, 2003

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1.0 PROJECT STATEMENT

1.1 Need

The San Solomon Springs System is located in the Toyah Basin at the foothills of the Davis Mountains near Balmorhea, Texas. The system includes Phantom Lake, San Solomon, Giffin, Saragosa, and Sandia springs and several other minor springs at higher elevations to the south and southwest (Figure 1). The springs are important aquatic habitat for many local wildlife species, including two federally endangered fish species, the Comanche Springs pupfish (Cyprinodon elegans) and the Pecos gambusia (Gambusia nobilis). These springs are also an important source of municipal and irrigation water for the communities in the Toyah Basin. Phantom Lake Spring is in Jeff Davis County, while the other major springs in this system are in Reeves County. The Reeves County Water Improvement District #1 (District) diverts water from the springs by using a system of canals to irrigate fields in the area. The Jeff Davis Underground Water Conservation District (District) has authority to permit and regulate groundwater in Jeff Davis County.

The general physiographic setting of the San Solomon Springs System is that of a largely alluviated, arid, and karst terrain. The aridity of the region restricts the available habitat for spring-dependent species and limits the available recharge to replenish and maintain spring flow. Pumping of the regional aquifer has significantly affected other springs in the area, including Comanche Springs near Fort Stockton, but it is not suspected to be the only cause of recent low flows at Phantom Lake Spring (Ashworth and others, 1997). The ecological importance of the springs in this area is very significant, as demonstrated by the occurrence of rare species endemic to the springs (Table 1).

Table 1. List of rare species endemic to the San Solomon Springs System.

San Solomon Springs System		
Species Occurrence	Scientific Name	Federal Status
Comanche Springs pupfish	Cyprinodon elegan	Endangered fish
Pecos gambusia	Gambusia nobilis	Endangered fish
Diminutive amphipod	Gammarus Hyalelloides	Species of Concern (may be extinct)
Undescribed amphipods	Gammarus sp.	Species of Concern
Brunes springsnail	Tyronia brunei	Species of Concern (may be extinct)
Phantom springsnail	Tyronia cheatumi	Species of Concern
Phantom Cave snail	Cochliopa texana	Species of Concern
Pecos assiminea (snail)	Assiminea pecos	Candidate species

Phantom Lake Spring has experienced significant decline in discharge over the past several drought years. In 1999, flow dwindled to just a trickle. Historical records indicate that spring flow declined from more than 10 cubic feet per second during the 1930s, to one cubic feet per second during the drought of 1996 to 1998, to less than 0.05 cubic feet per second in 1999. Currently, there is no flow out of Phantom Lake Spring and a dam has been constructed to provide habitat for the species (Figure 2). To support the surface population of species a submersible pump was installed by the Bureau of Reclamation in May 2001 to pump water from inside the cave to the surface.

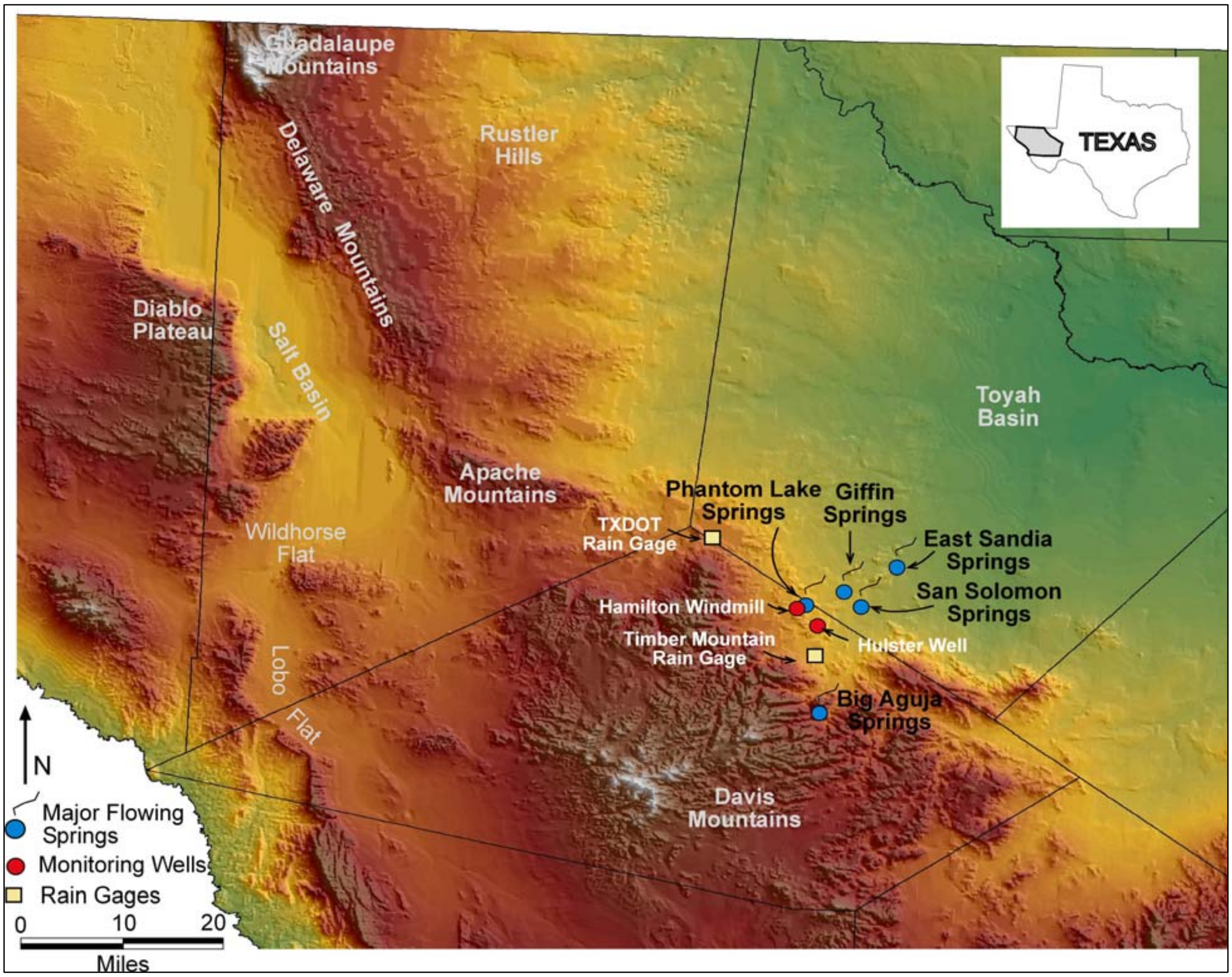


Figure 1. Map of the physiographic features, major flowing springs, rain gages and monitoring wells in the study area.

Figure 2. Phantom Lake Spring.

At the request of the District, the Texas Water Development Board (TWDB) conducted a local well monitoring study and concluded that recent flow declines in Phantom Lake Spring and San Solomon Springs was the result of diminished recharge due to the extended dry period rather than from groundwater pumpage (Ashworth and others, 1997). Although certainly a factor, drought alone is unlikely the only reason for declines because the drought of record in the 1950s had no effect on the overall flow trend at Phantom Lake Spring. Ashworth and others (1997) also noted that their cursory study did not identify groundwater pumpage as directly affecting spring flow but thought it important to recognize that the improper placement of new wells could definitely have a detrimental effect on the springs.

The exact cause or causes for this decline in spring discharge are unknown. Some of the obvious reasons are groundwater pumping of the supporting aquifer and decreased recharge of the aquifer from drought. Unfortunately, the supporting aquifer for the springs is not well defined. Recent studies support that although the spring is locally recharged by runoff from the Davis Mountains (resulting in the flow spikes) the base flow comes from a regional groundwater system (LaFave and Sharp, 1987; Schuster, 1997; and Sharp and others, 1999). The source water to the springs is likely from groundwater flowing through the Apache Mountains with recharge areas in the Wild Horse Flats Basin to the northwest of the Toyah Basin. Sharp and others (1999) further proposed that the declines in flows are most likely the result of groundwater pumping in this region. This study further investigates the link between groundwater pumping and spring-flow decline.

Exploration of Phantom Cave by cave divers has led to additional information about the nature of the spring and its supporting aquifer (pers. comm., Bill Tucker, Tucker's Dive Shop, 1999). Beyond the entrance, the cave has a substantial conduit that transports a large volume of water generally from the northwest to the southeast, consistent with regional flow pattern hypothesis (Figure 3). Over 8,000 feet of the cave conduit have been mapped so far. In addition, flows have been measured and are in the 25-cubic feet per second range. The relatively small flow at Phantom Lake Spring is essentially an overflow of a larger flow system underground.

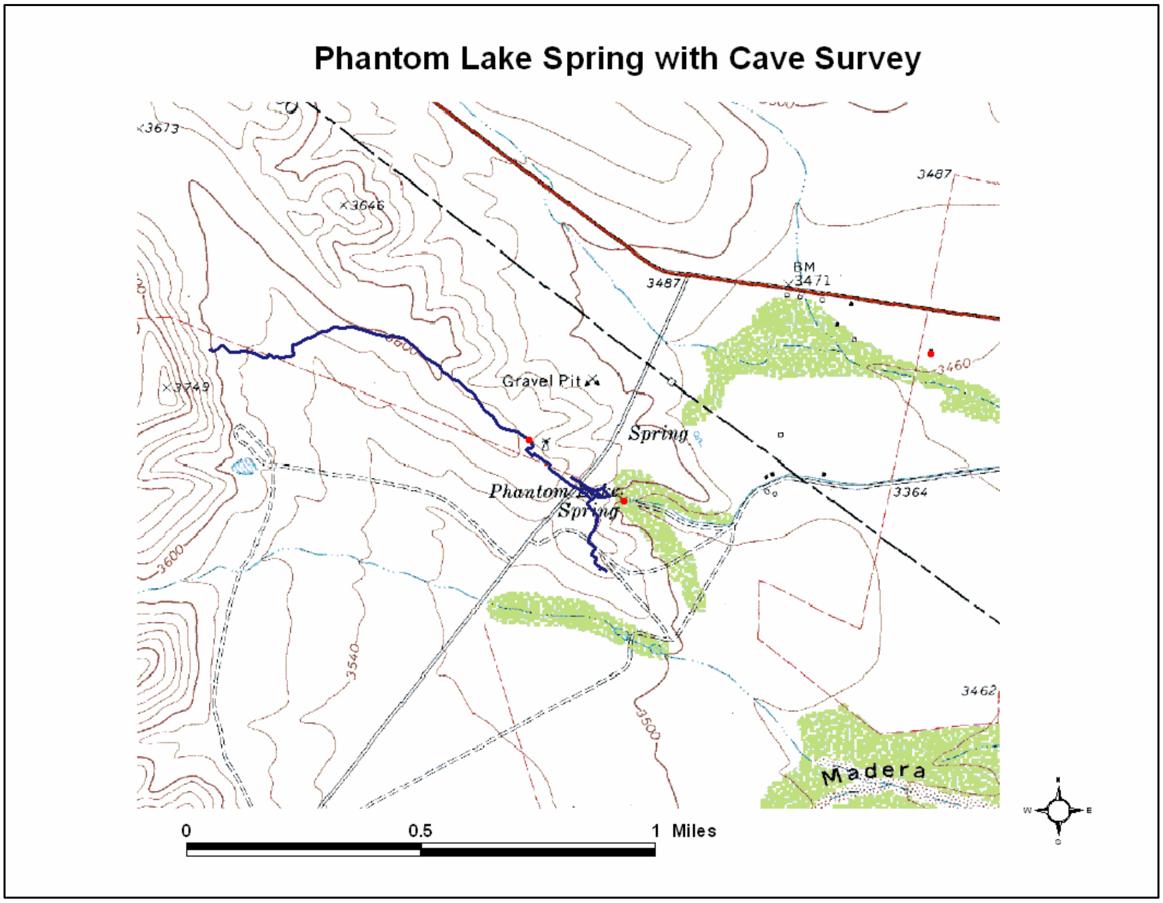


Figure 3. Topographic map of Phantom Lake Spring vicinity overlain with cave survey map (Tucker, 1996).

Although long-term data are scarce, flows from San Solomon Springs have declined somewhat over the history of record, but not as much as Phantom Lake Spring (Schuster, 1997; Sharp and others, 1999). Some recent declines in overall flow have likely occurred due to drought conditions and declining aquifer levels. Discharges from San Solomon Springs are usually in the 25 to 30 cubic feet per second range (Ashworth and others, 1997; Schuster, 1997) and are consistent with the theory that the water passing under Phantom Lake Spring are later discharged at the San Solomon Springs. Giffin Springs maintains a near constant 3 to 4 cubic feet per second outflow (Ashworth and others, 1997). Similar water chemistry and near constant temperatures of about 26 degrees Celsius among these three springs support that their waters originate from the same source (Schuster, 1997).

The aquifer system that supports the springs is not well defined on a regional scale and groundwater pumping has not been investigated throughout the aquifer system. The origin of the groundwater that flows through the springs is complex and in need of further study. In addition, spring flow information for the region needs to be compiled to determine the long-term decline of the spring system.

The most significant threat to the continued existence of the endangered Comanche Springs pupfish and Pecos gambusia is the loss of spring habitat due to the decline of groundwater levels of the supporting aquifers (U.S. Fish and Wildlife Service, 1981, 1983). In addition, the unique ecosystems of these springs host locally endemic species that also depend on adequate spring flows. The opportunity for groundwater conservation and management can only occur with an appropriate understanding of the aquifers that provide water to the springs.

1.2 Previous Works

Several researchers have studied the hydrogeology and geochemistry of groundwater in the Trans-Pecos region (White and others, 1941; Harden, 1972; Couch, 1978; Hiss, 1980; Nielson and Sharp, 1985; Sharp, 1989; LaFave and Sharp, 1990; Uliana, 2000; Sharp, 1998; and Sharp and others, 1999). Most of the research focused on identifying the sources of the water for the springs in the area.

The U.S. Geological Survey, the U.S. Department of the Interior, and the Texas Board of Water Engineers cooperatively generated the most informative report of the geology of the Balmorhea area in 1941 (White and others, 1941). The authors of this publication believed that the spring waters of the San Solomon Springs system were derived from an interconnected system of fissures and solution passages in the Lower Cretaceous limestone. White first opined that the principal area of intake for the spring waters was the anticlinal valley that parallels the steep fronts of the Davis Mountains and the mountains west, northwest and southwest of the springs. They reported considerable increases in flow in the springs immediately after local, heavy rains.

On a larger scale, the Texas Board of Water Engineers completed a preliminary report on the geology and groundwater resources of Reeves County in the following decade (Knowles and Lang, 1947). This report referenced Phantom Lake, Giffin, and San Solomon as artesian springs and Toyah Creek, Saragosa, East Sandia, and West Sandia as gravity springs. Groundwater resources in Reeves County were studied in more detail and further discussed in the Texas Water Commission Bulletin 6214 volumes I and II (Ogilbee and Wesselman, 1962). While this report contains excellent historical records of pumpage in Reeves County, very little information concerning the springs was presented.

In 1969, preliminary research was started under the pretense of possibly creating an underground water conservation district in the immediate area surrounding the San Solomon Springs system (Harden, 1972 and Couch, 1978). These two researchers worked and collaborated to determine and describe the geohydrologic units and to collect, compile, and analyze all available data on the occurrence, development, and chemical quality of the groundwater in the region that contributed flow to the spring system. These were some of the earliest studies that suggested base flow to the springs probably originated to the west, around the Apache Mountains in Culberson County. Couch (1978) postulated that water from the Capitan Reef aquifer west of the Pecos River could flow southeast through the faults into the down-faulted Lower Cretaceous aquifer. He observed that flow in Phantom Lake Spring increases considerably after 24 hours of heavy rainfall and flow in San Solomon and Giffin springs increases another 24 hours later than Phantom Lake Spring. The changes that occur in all three springs during storm flow include increases in flow, lowering of water temperature, decreases in mineral content, and increases in turbidity. He thought that the springs hydrologic system are controlled by a constant base flow component that is fed by recharge from the volcanic terrain, alluvium and underflow from the stream gravels and a storm flow component that consists of extensive system of cavities and channels in superposition of the constant flow system. Harden (1972) delineated a “primary area” of contribution to the springs and indicated that a total groundwater pumpage of 150,000 gallons per day or more would likely affect spring flow.

Hiss (1980) reported on the groundwater movement in the Permian Guadalupian aquifer system in southeastern New Mexico and western Texas. He concluded that a combination of factors controlled groundwater flow distribution (1) regional and local tectonics, (2) evolution of the landscape, (3) relative transmissivities of the aquifers, (4) the amount of recharge, and (5) exploitation of groundwater and petroleum over the last five decades. He indicated that groundwater moved east and southeastward through the shelf (Capitan Reef and associated limestone) and basin aquifers (Delaware Mountain Group).

Nielson and Sharp (1985) suggested that the high-permeability of the reef facies of the Capitan aquifer can provide a conduit for flow through the preferentially west–east aligned faults through the Apache Mountains. Using computer simulation, they reported that 2,850 acre-feet per year of water could potentially come from the southern portion of the Salt Basin that is however much less than the average flow of 33,000 acre-feet per year in the springs.

LaFave and Sharp (1987) observed water quality from wells in the Davis Mountains is markedly dissimilar from the springs. They reported that the groundwater from the Davis Mountains is fresh containing less than 500 milligrams per liter total dissolved solids while the spring waters have total dissolved solids of 2,000 to 2,400 milligrams per liter. They also pointed out that the sodium, chloride and sulfate present in the Phantom Lake Spring water suggest interaction with evaporate sequence that is not found between the Davis Mountains and the spring. From limited isotope measurements, they observed that the spring has a delta (∂) Oxygen-18 (18O) value of –8.52 parts per thousand (o/oo) Standard Mean Ocean Water (SMOW) compared to a ∂18O value of -5.71 o/oo SMOW from a spring on Limpia Creek in the Davis Mountains. A corrected Carbon -14 (C-14) age for one sample from the spring was found to be 8,954 plus or minus 235 years before present. This information led them to suggest that the spring water could not be of local origin but more likely from higher elevations or cooler Pleistocene times. They also postulated that during a storm, spring water could comprise as much as 73 percent from the Davis Mountains and 27 percent from a steady source, the Capitan aquifer and associated limestone through a fault conduit through the Apache Mountains.

Uliana (2000) carried out a detailed investigation of the spring waters using stable isotope ratios of Strontium ($^{87}Sr/^{86}Sr$), hydrogen ($\partial^{2}H$) and oxygen ($\partial^{18}O$). He indicated that the spring waters were partially recharged from a regional system in the southern Salt Basin and flows through the Apache Mountains into the Toyah Basin. Fracture trends in the bedrock largely control the regional flow system. Using PHREEQE geochemical model, he indicated that 28 to 43 percent of the spring water could have been recharged from base flow from the west and 57 to 72 percent from local meteoric recharge in the Davis Mountains.

In the past decade, TWDB conducted a small study to evaluate the diminished spring flows in the Toyah Creek Valley (Ashworth and others, 1997). The conclusion reached from this study indicated recent declines in spring flow were more likely the result of diminished recharge due to an extended dry period rather than from ground-water pumpage. Although it did stress the drilling of high-capacity wells should be preceded by an expert hydrogeologic evaluation.

On a local scale, the "Springs of Texas" is an excellent reference to obtain a historical perspective on the individual springs within the San Solomon Springs System (Brune, 1981). For additional information on Phantom Lake Spring and the history of water use in the area, the U.S. Bureau of Reclamation has posted a summary of their involvement in the Balmorhea Project on their web site: http://www.usbr.gov/dataweb/html/balmorhe.html (Bogener, 1993). In addition, Argyle Tucker III, a cave diver, reported on his findings from several dives completed between December 1995 and October 1996 of the Phantom Lake Spring cave system (Tucker, 1996).

Mace and others (2001) was a useful compilation of papers to review various components of the surrounding aquifers that may contribute groundwater to the San Solomon Springs flow system.

1.3 Objectives

The primary objectives of the study were to study the hydrogeology of source aquifers for the San Solomon Springs System and to evaluate the effect, if any, of groundwater well usage on spring flow. This included work to:

- delineate the recharge and discharge areas of springs,
- delineate groundwater flow paths,
- estimate local versus regional recharge to the springs and aquifers,
- determine hydraulic properties of the aquifers,
- describe the interaction between surface water and groundwater,
- evaluate impacts of meteorological conditions
- calculate water balances, and
- evaluate impacts on springs from regional groundwater pumping.

2.0 APPROACH

2.1 Overview

We conducted the study in two phases. The purpose of Phase I was to expand our database of monitoring wells in the San Solomon Springs System region, to conduct pumping and other groundwater flow studies, and determine the connectivity of the springs to the local and regional flow system. We collected and analyzed geochemical water samples to study the hydrogeologic signature of the source aquifer and its complex flow regime.

Phase II was necessary to further understand the complex groundwater regime and focused on aquifer characterization and further delineation of the aquifer source system. Phase II refined recharge, infiltration, precipitation, and other groundwater modeling data to further understand the complex hydrological regime.

The tasks for Phase I (Year 1) included:

- implementing a spring and groundwater monitoring program to document changes in discharge;
- assessing the spring's geochemical and physical hydrology;
- performing geochemical assessment of regional well sites, including analyses for stable and radiogenic isotopes;
- locating existing wells for regional monitoring within the aquifers that are source water to the spring;
- delineating Phantom Lake Spring's drainage basins and flow paths;
- measuring water levels throughout the study area and develop maps of water elevations and flow paths;
- conducting pumping and groundwater flow studies at well sites to explore the degree of connectivity to the spring; and
- evaluating the impacts of regional groundwater pumping on spring flows.

The tasks for Phase II (Years 2 and 3) included:

- performing additional geochemical assessments of regional well sites, including analyses for stable and radiogenic isotopes;
- extending local and regional geological investigations through acquisition and interpretation of oil and water log data; and
- conducting an aquifer characterization study to accurately determine hydrogeological characteristics.

2.2 Methodology

In the following sections, we have outlined the equipment, software, and methods used to meet the objectives and goals for this investigation. When appropriate, we followed standard industry protocol during routine scientific procedures. The mention of brand names for the equipment and software used does not constitute endorsement by TWDB or its staff members.

2.2.1 Spring and Groundwater Monitoring

To document changes in discharge to the springs in the San Solomon Springs System and changes in local groundwater levels, we established long-term monitoring of water levels during Phase I and Phase II of this project. Water-level monitoring equipment included long-term automatic recording devices (transducers) and stationary measurement equipment such as staff gages.

2.2.1.1 Spring monitoring

During the duration of this study, the springs that were still flowing within the San Solomon Springs System included Phantom Lake, San Solomon, Giffin, and East Sandia. West Sandia and Saragosa springs had ceased to flow. Monitoring the springs served to:

- establish a baseline;
- help determine possible connectivity of the springs by comparing relative changes in water levels;
- provide insight to possible mechanisms that trigger changes in flow patterns; and
- furnish a tool to analyze long-term trends.

To monitor changes in discharge and water levels, we used two basic types of monitoring equipment: transducers and staff gages. After some research, we selected Solinst brand transducers because of their lower overall cost, multiple parameter options, ease of use, and compact size when compared with other brands. Solinst LTC Leveloggers® are capable of recording water levels, temperature, and conductivity parameters (Figure 4). The probe is compact (0.875 inches by 10.2 inches), is composed of stainless steel, and uses an infrared data transfer that allows personnel to directly download data onto a laptop. Because the direct-read cable system is not vented, we purchased and installed two barometric transducers to compensate water-level measurements for changes in atmospheric pressure. Water-level measurement sampling options with this brand transducer are linear or event-based and were set to record every 15 minutes to hourly.

Figure 4. Example of Solinst LTC Levelogger with direct read cable and probe.

2.2.1.1.1 PHANTOM LAKE SPRING

Phantom Lake Spring (Figure 1), state well number (SWN) 52-02-405, is located to the west of San Solomon Springs along the hydrogeologic contact of the Edwards-Trinity (Plateau) and the Cenozoic Pecos Alluvium aquifers (Figure 5). Monitoring water-level and water temperature changes at Phantom Lake Spring was instrumental in attempting to understand the causes of water-level declines and possible recharge events that may impact living conditions for the endangered species still occupying the spring. On April 24, 2001, we installed a Solinst LTC Levelogger in the northern arm of the cave to avoid interference with the pump located in the western arm. The monitoring location of the transducer was approximately 55 feet from the pre-existing staff gage located inside the gated entrance. Due to adverse water conditions, conductivity (the measurement of the concentration of ions, empirically related to total dissolved solids) and temperature recordings from the original Solinst LTC Levelogger installed in 2001 became unstable. Periodic inspection of the probe indicated a build-up of corrosive materials that eventually adversely affected the recording capability of the conductivity parameter of the transducer. On August 20, 2002, we purchased and installed a replacement. The water level parameter of the original probe was tested and determined to be accurate. We maintained the original probe as an emergency back up.

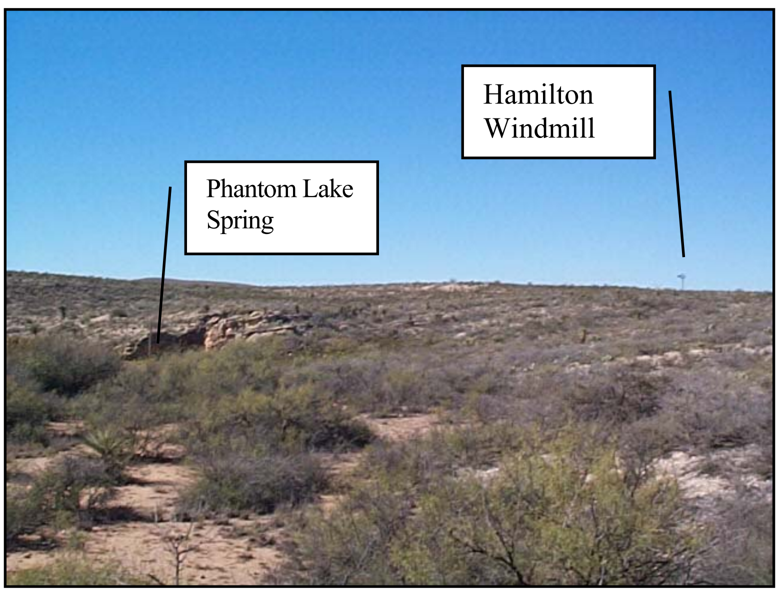


Figure 5. Phantom Lake Spring located at the contact of the Edwards-Trinity (Plateau) and Cenozoic Pecos Alluvium. The Edwards-Trinity (Plateau) appears as the ridged area in the background with the alluvium in the lower left-hand corner.

In addition to the continuous monitoring equipment, we purchased three staff gages from Forestry Supplies. After discussions with U.S. Fish and Wildlife Service (FWS) and Texas Parks and Wildlife Department (TPWD), it was determined the existing staff gages had become unstable and a sturdier staff gage would be beneficial. In November 2002, we supported the existing staff gages to their posts with zip-ties. In June 2003, we installed one of the newly purchased staff gages at Phantom Lake Spring.

2.2.1.1.2 SAN SOLOMON SPRINGS

San Solomon Springs (Figure 1), SWN 52-02-611, are located in Balmorhea State Park. Water from the springs discharges from the Cenozoic Pecos Alluvium aquifer into a swimming pool (Figure 6). Previous investigations indicate San Solomon Springs may be experiencing a slower, subtler decline in water levels over time. Long-term monitoring will allow us to estimate the rate of decline. On May 14, 2002, we installed a Solinst LTC Levelogger in a 1.5-inch PVC pipe mounted on the submerged, gated, fenced area near the south gate on the eastern side of the main pool (approximately 50 feet from the diving board). Two separate gates located on the eastern portion of the pool periodically release water. The northern gate supplies water for irrigation. The southern gate maintains water levels in the man-made cienega on the premises of the park. Water diverted from the southern gate eventually flows into Balmorhea Lake located to the northeast of the park. During the monitoring program at San Solomon Springs, we coordinated with park staff to document when releases occurred.

Figure 6. San Solomon Springs at Balmorhea State Park. Star indicates location of transducer (Insert shows a close-up of the PVC encasing the transducer on January 15, 2003, at a time when the pool was drained for maintenance).

2.2.1.1.3 GIFFIN SPRINGS

Giffin Springs, SWN 52-02-610, are located within 800 feet northwest of San Solomon Springs (Figure 1). Previous studies indicate a close relationship between these two springs and their source waters. Water from Giffin Springs discharges from the Cenozoic Pecos Alluvium aquifer into a natural pool (Figure 7). After receiving permission from Reeves County Water Improvement District #1, we installed a staff gage on August 21, 2002 in the main pool area to monitor changes in water levels over time (lat 30° 56” 43’ N; - 103° 47” 28’ W). Around the beginning of August 2002, the United States

Geological Survey (USGS) installed a continuous monitoring station at Giffin Springs. The new USGS real-time gaging station (ID 08427000) is located approximately 300 feet from the main pool along the Reeves County Water Improvement District #1 irrigation canal (lat 30°56’45” N; long -103°47’23” W).

Figure 7. Giffin Springs (picture on the left). Installation of staff gage by Ray Mathews (picture on the right).

2.2.1.1.4 East Sandia Springs

East Sandia Springs, SWN 52-03-115, are located northeast of San Solomon Springs (Figure 1). While East Sandia Springs are located down gradient from Saragosa and West Sandia springs, they are one of the only remaining springs down dip from San Solomon Springs that still maintain water in its wetland area. Saragosa and West Sandia springs did not exhibit sufficient flow to establish a monitoring site for the duration of this study. On August 20, 2002, a staff gage was installed in East Sandia Springs (lat 30° 59” 28’ N; long -103° 43” 44’ W) after consultation with representatives from the Nature Conservancy, the property owners (Figure 8).

2.2.1.2 Groundwater monitoring

To determine possible impacts of pumpage to discharge at Phantom Lake Spring and the other springs in the San Solomon Springs System, we continuously monitored water levels at wells in the immediate vicinity of the springs during Phase I and Phase II of this project.

2.2.1.2.1 Hamilton Windmill

Hamilton Windmill, SWN 52-02-401, is located within 0.25 miles up gradient from the Phantom Lake Spring (see Figures 1 and 5). According to Texas Water Development Board (TWDB) well schedule notes, the drill date is unknown. However, the well existed before 1969. A local resident told TWDB personnel that he believed there is a connection to Phantom Lake Spring because when the “well was worked on, it muddied up the spring.” On February 6, 2001, a Delta 591 transducer with a vented cable was installed and connected to a Stevens AXS logger unit on a temporary basis. This

Figure 8. East Sandia Springs and surrounding wetlands (picture on the left). Installation of staff gage by Ray Mathews (picture on the right).

earlier set-up collected water-level readings only. On August 30, 2001, we installed a Solinst LTC Levelogger that recorded water levels, temperature, and conductivity readings.

2.2.1.2.2 HUELSTER WELL

A complex of municipal wells is located within 1.25 miles to the south-southeast of Phantom Lake Spring. This complex includes a well operated by the City of Balmorhea (SWN 52-02-407) and two wells operated by Madera Valley Water Supply Corporation (SWN 52-02-404 and 52-02-408). We selected a well located within 0.25 miles to the north of this pumping center to observe changes in water levels possibly due to municipal pumping (Figure 1). On April 25, 2001, we installed one Solinst LTC Levelogger and one Solinst LT/F15 Barometric transducer in the Huelster well, SWN 52-02-403.

2.2.2 Potentiometric Surface Mapping

We used water-level maps to analyze probable groundwater flow paths. In Open File Report 97-03, TWDB developed a water-level map for the area in the immediate vicinity of the springs (Ashworth and others, 1997). In February 2001, we re-measured many of the same wells in Jeff Davis and Reeves counties. The purpose was to establish current conditions and to uncover possible changes in water levels and flow directions around the main springs. We analyzed additional water level measurements encompassing wells in Culberson, Jeff Davis, and Reeves counties to reflect regional trends.

2.2.2.1 Water-Level Measurement and Mapping

TWDB staff followed standard protocol for measuring water levels as outlined in TWDB Users Manual UM-52 (TWDB, 1994) and UM-50 (TWDB, 1998). TWDB adopted the procedures from methods accepted and used by the United States Geological Survey (USGS) in 1988. We primarily measured water levels based on the calibrated electric sounder (E-line) method with a few measured by the graduated steel tape method. We reported all measurements as depth to water in feet from land surface. The data used in the development of maps for this report were from field measurements taken expressly for this project or from data stored in the TWDB Groundwater Database. We imported water-level data points into contouring and 3-dimensional surface mapping software, such as Surfer® 8 or 3-D Spatial

Analyst for Arcview®, and interpolated the data using a geostatistical gridding method known as kriging.

2.2.2.2 Global Positioning System Surveys

The well and spring elevations stored in our groundwater database are mainly derived from an interpolation method using 1 to 24,000 scale topographic sheets and depending on the contour level may be offset as much as 5 to 40 feet. In order to correlate water levels from our monitoring program at the springs to those in the surrounding wells, surveys of the springs and monitoring wells were necessary to obtain accurate spatial and vertical coordinates. We used Global Positioning System (GPS) units for the surveys to (1) set up a more permanent benchmark at Phantom Lake Spring, (2) to determine the elevations of the individual spring orifices, and (3) to determine the current water levels at the springs and monitoring wells so we could correlate water elevations to the data collected during our monitoring program. By using one GPS unit as a base station and the other as a roving unit, it is possible to get the relative elevation difference between points to a high degree of accuracy that approaches other methods, such as a traditional survey which utilizes a surveyor's level or by using the total station methodology. In addition, the horizontal position can be determined within centimeter accuracy. We used a Trimble GPS Pathfinder® Pro XRS system to conduct the survey and processed the data with Trimble Pathfinder® software. We used a Sokkia B20-type automatic surveyor level for mapping detailed information at various locations in and around the springs.

Before departing for the study area, we identified pre-existing benchmarks near Phantom Lake Spring using the National Geodetic Survey (NGS) web site (http://www.ngs.noaa.gov/datasheet.html), which reports the location, description, and condition of benchmarks. A NGS benchmark labeled "3471" was located 3.4 miles west of Toyahville on Highway 290 and verified by the US Power Squadron in 1996 (lat 30° 56" 30' N; long -103° 50" 37' W). The orthometric height was determined by differential leveling and adjusted by the National Geodetic Survey in 1992 (NAV88 elevation: 3471.72 feet). The vertical order of this benchmark was given a "Code A", indicating a distribution rate of 0.0 through 1.0 millimeters per kilometer. The NGS benchmark is located approximately one mile from Phantom Lake Spring.

On March 20, 2002, TWDB staff arrived in the Balmorhea area to survey Phantom Lake Spring and visually verified the location of the USGS benchmark at the spring. On March 21, 2002, TWDB staff located the NGS benchmark on Highway 290. It is located along a fence line, 3.4 miles west of the Toyahville post office and approximately 175 feet northwest of a steel culvert (Figure 9).

Because of the local topographic relief, we established the GPS base station some distance away from Phantom Lake Spring on the top of a hill (Figure 10). Once the GPS base station started logging its position, we placed the rover unit on the NGS Highway 290 benchmark for 45 minutes in order to gather enough data for the required accuracy. We maintained contact with at least five satellites throughout the establishment of the Phantom Lake Spring benchmark. This assured a high degree of accuracy for x,y and z data coordinates from the GPS survey for this location.

Figure 9. Location of NGS benchmark on Highway 290.

Figure 10. Figure on the left shows the establishment of the GPS base station. Figure on the right shows the location of the new GPS surveyed benchmark at Phantom Lake Spring.

Between June 23 and June 27, 2003, TWDB staff revisited the Balmorhea area to survey the location of the remaining springs and monitoring well sites using the same equipment. We followed the same basic procedures described above and allowed at least 45 minutes at each survey point to lock in a minimum of five satellites. On June 24, 2003, we surveyed the Hamilton windmill and Huelster monitoring well using the same NGS benchmark on Highway 290 (NAV88 elevation 3471.72 feet). We surveyed San Solomon, Giffin, and East Sandia springs on June 25, 2003, using a benchmark identified as B.S.P. 1 located within Balmorhea State Park inside the fence line along Highway 290 to the north of the San Solomon pool (lat 30° 56” 40’ N; long -103° 47” 19’ W). The elevation inscribed on the benchmark was 3318.63 feet. Additional information describing the accuracy of the elevation was not available. This benchmark was not inventoried with the NGS.

In addition to surveying the water level at each of the spring monitoring sites, we documented the location of six of the flowing springs at San Solomon Springs. After establishing a temporary benchmark near the pool, a scuba diver located each of the orifices and positioned a range pole so that each orifice could be surveyed with a surveyor’s level. No spring openings were discernable from diving surveillance within the immediate area of the monitoring site at Giffin Springs. After establishing a temporary benchmark on the north bank of the pool at Giffin Springs, we surveyed the water level of the staff gage, as well as eight other locations in the pool. Water conditions at East Sandia were not conducive to diving. Surveying the depth to the springs or surveying in a cross-sectional profile was not feasible at this location. We used ArcGIS® software to process and to portray the results of our bathymetric surveys.

2.2.3 Geochemical Assessment

Analysis of elemental and isotopic compositions of groundwater is critical to our understanding of the source areas and groundwater flow system. Groundwater acquires distinct chemical and isotopic characteristics as it flows through pore spaces of aquifer materials, fault conduits, or moves upward in discharge areas. We use these characteristics to help identify the chemical processes that modify the initial groundwater composition or recharge.

Prior to selecting wells for groundwater sampling, we hypothesized potential groundwater flow paths from the inferred source areas from the Davis Mountains (southern flow path) and the Apache Mountains and beyond (western flow path) to the Phantom Lake spring. We used potentiometric surfaces from the intervening aquifers and lineament distribution patterns in the area to outline potential flow paths to the spring. We used these flow paths to select the wells for sampling. We took groundwater samples from wells completed at shallow depths where the water is presumably fed from recent recharge events. We also took groundwater samples from wells completed at deeper intervals near discharge areas where the water had longer residence time from having to flow through deeper stratigraphic units, thus retaining some of the chemical characteristics inherent to the aquifer mineralogy. In order to get a better appreciation of the chemistry and isotopic compositions of the groundwater in the Permian limestones, we also sampled wells northwest of the Apache Mountains. In addition, we have reviewed water quality data from wells completed in the Cretaceous and the Permian rocks in the four counties adjacent to our study area. We reported ion ratios of the groundwater from each of the geologic units to observe whether any unique ratios emerged particular to any unit.

To assess the geochemistry of the San Solomon Springs System, we collected water quality information during Phase I and Phase II of the project, including:

- field measurements of pH, temperature, and conductivity;
- continuous monitoring of temperature and conductivity; and
- groundwater and springs water samples for major cation and anion analysis and isotopic analyses for Oxygen-18, Deuterium, Tritium, Carbon-14, and Sulfur-34.

The analysis of the water quality information included (1) grouping the groundwater and the spring water samples into geochemical facies using piper diagrams, (2) determining potential water-rock interactions that might occur during groundwater flow, (3) geochemical modeling to determine geochemical evolution of the waters, and (4) comparing observed changes in water chemistry to rainfall data. We then used water-quality modeling information to help delineate the flow paths within the springs' system:

- to determine any effects that local rainfall may have on discharge,
- to possibly explain the processes that lead to the decline in discharge to Phantom Lake Spring, and
- to assist in suggesting the location of existing wells for regional monitoring within the aquifers that are source waters to the San Solomon Springs System.

2.2.3.1 Sampling Techniques

We followed standard protocol for water quality sampling as outlined in TWDB Users Manual UM-51 (TWDB, 1996). This manual includes the methodology for sampling, as well as the equipment needed to properly collect and preserve the sample before delivery to the laboratory.

We obtained isotope-sampling procedures from the analytical laboratories: Beta Analytic, Inc., Miami, Florida; The Tritium Laboratory, University of Miami/RSMAS, Miami, Florida; and Coastal Science Laboratories, Austin, Texas. We collected all isotope samples in sterilized plastic bottles, sealed the bottle with tape, and placed the samples on ice. We used Teflon or Tygon tubing for collecting samples from wells that we pumped. For spring samples, we dipped the sample bottles below the water surface, close to spring source. All field parameters, such as pH, conductivity, and temperature, were stable before sampling. We collected the Oxygen-18 and Deuterium samples in 250-milliliter plastic bottles that we tightly sealed and taped. They did not require refrigeration. The Sulfur-34 samples did not require preservation and were collected in 500-milliliter plastic containers. We collected the Carbon-14 samples in wide-mouth Nalgene or equivalent one-liter containers that we cleaned by flushing the bottle with the sample water. We preserved the samples with four to five milliliters of sodium hydroxide (NaOH) and tightly sealed and taped the container shut. The Tritium samples did not require filtering or preservation. They were collected in one-liter high-density polyethylene bottles. We removed wristwatches before sampling to avoid contamination of the sample by Tritium emitting luminous dials found on some brands of watches. We collected the samples outdoors and minimized contact with ambient air before tightly sealing and taping the sample bottle.

In addition to collecting water quality samples for laboratory analysis, we recorded and documented field measurements of pH, temperature, and conductivity using Thermo Orion© field equipment. We used the standard operating procedures provided with the equipment during the collection of field measurements. Procedures included daily re-calibration of the equipment using approved chemical standards and the proper pre- and post- maintenance and storage of the probes and field sampling equipment.

The Solinst LTC Leveloggers also collected temperature and conductivity. We used the standard operating procedures provided with the equipment and re-calibrated the equipment on an annual basis using approved chemical standards.

2.2.3.2 Laboratory Methods

The Lower Colorado River Authority (LCRA) Environmental Laboratory Services in Austin, Texas, conducted the standard major cation and anion analysis. Analysis of all cation-anion groundwater and spring samples was by Ion Chromatography-Mass Spectrometry (ICP-MS).

Beta Analytic Inc. conducted the isotope analyses of Carbon-14 (Carbon-14 Dissolved Inorganic Carbon) using an accelerator-mass-spectrometer (AMS). They presented their results as apparent radiocarbon age before present (B.P., where present = 1950 A.D.) and percent of the modern standard (pmC). Carbon-13 to Carbon-12 ($^{13}C/^{12}C$) ratios were measured with reference to the Pee Dee Belemnite (PDB) standard.

The Tritium laboratory of the Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Florida, analyzed for Tritium (^{3}H) using the low-level Tritium method by gas proportional counting. The Tritium concentrations were expressed in TU, where one TU indicates a Tritium to

Hydrogen ratio of 10 to 18.

Deuterium (^2H), Oxygen-18 ($^{18}O/^{16}O$), and Sulfur-34 ($^{34}S/^{32}S$) analyses were conducted at the Coastal Sciences laboratory in Austin. Oxygen-18 isotopes were analyzed on a VG Micromass SIRA Series II mass spectrometer using the carbon dioxide (CO^2) equilibration method (Epstein and Mayeda, 1953). Deuterium was measured by chromium or zinc reduction to Deuterium gas on a Micromass 602D mass spectrometer. Sulfur-34 was analyzed by extracting sulfur dioxide (SO^2) from settled barium sulfate ($BaSO_4$) using a mass spectrometer VG Model 10, Series II.

2.2.3.3 Geochemical Analyses

We used NETPATH (net geochemical reactions along a flow path) computer code available through the public domain to determine geochemical evolution of the waters (Plummer and others, 1994). NETPATH uses equations for chemical mass balance, electron balance, and isotope mass balance to account for net geochemical reactions between the initial (recharge area) and the final water (discharge area) along a flow path. The geochemical reactions are constrained by using a number of appropriate products, reactant minerals, and gases to reflect the geology of the study area. We then simulated each of the reaction models to reach the measured isotope values of the final water by adjusting the initial Carbon 14 (^{14}C) activity and accounting for all isotope fractionation.

For evaluating the chemical characteristics between the springs and the potential source water wells that fall along the inferred flow path, we plotted the results of both the current and the historical water chemistry information on a Piper diagram. We also plotted the spatial locations of the wells and springs using ArcView® geographical information system (GIS) software. In addition, we attempted to flag and document unexplained changes in the geochemical parameters measured by our field equipment against rainfall data and changes in water levels.

2.2.4 Aquifer Characterization (Physical Properties)

Aquifer characterization is the process of quantifying the physical features of an aquifer that control groundwater movement in the subsurface. Understanding the structural geology, the composition of the material in the subsurface, and the physical properties of that material are fundamental steps in characterizing an aquifer. The methods and approaches included pump tests, historical studies, field research, and well log interpretation.

To understand the structural geology of the region we researched previous field studies and reports, verified geologically exposed structure in the field, and interpreted well logs. Due to the complexities and inter-relationships of the geologic formations in the study area due to faulting, dissolution, and fracturing, our goal was to provide a simplified interpretation encompassing the general trends observed.

We expanded our understanding of the physical properties of the subsurface through aquifer tests conducted in the study area. By pumping a well and recording the change in groundwater levels over time, draw down and recovery, the hydraulic properties of an aquifer - specifically transmissivity, hydraulic conductivity, and storage coefficients - can be estimated from the drawdown observations. These terms numerically describe the propensity for water to flow within the system.

2.2.4.1 Structural Geology

We did a careful search for literature pertaining to the geology in the Balmorhea area of western Texas. Geologic information in the area around Phantom Lake Spring and Balmorhea is relatively limited (White and others, 1941; Hart, 1992; and Sharp, 2001). Other geologic resources include both the Fort Stockton Sheet and the Pecos Sheet of the Geologic Atlas of Texas produced by the Bureau of Economic Geology at the University of Texas at Austin in 1982. These maps are at a scale of 1 to 250,000. Details of geologic subtleties such as minor faulting, fracturing, and karstification within the Phantom Lake Spring and the San Solomon Springs areas are not visible because of the scale. These geologic subtleties are important elements in the formation and flow characteristics of the springs.

Because faulting appears to have some significant influence on the position and flows of the various springs in the area, we traveled to the Balmorhea area on January 15 to 17, 2003, and visually examined, documented, and researched the faults associated with the San Solomon Springs System. In addition to field research, we evaluated approximately eighty well logs from Culberson, Jeff Davis, and Reeves counties. We plotted the data gathered from the well logs and our groundwater database and further analyzed the information using Surfer® 7, Autodesk Map™, Microsoft® Excel, and ESRI® Arcview 3.2 software.

Since previous studies have inferred the source water to the springs is likely from the Apache Mountains vicinity with recharge areas in the Wild Horse Flats Basin to the northwest of the Toyah Basin, we obtained preliminary geologic structure data and cross-sections from LBG-Guyton and Associates. TWDB has contracted with LBG-Guyton and Associates to complete a Groundwater Availability Modeling (GAM) study of the Igneous aquifer and parts of the West Texas Bolsons aquifer. The projected completion date of the final report and model is August 2004.

2.2.4.2 Pumping Tests

We conducted two single-well pumping tests, one each in Jeff Davis and Culberson counties (Figure 11). We also monitored a pumping test on the Huelster well in Jeff Davis County. The basic procedure was as follows:

- We measured the test well for depth to water on at least two occasions to assure a static water level before starting the test.
- After starting the pump, we recorded changes in water levels at selected time intervals using an electronic air/water interface probe and/or a pressure transducer that reads the amount of water above the instrument in feet.
- We monitored water discharge rates periodically throughout the test to confirm that we maintained a constant pumping rate.
- At the end of the pumping phase of the test, we shut the pump off. During the water level recovery phase, we measured and recorded water levels at selected time intervals.

To evaluate the relationship of draw down time and pumping rate we referenced various interpretative models depending on the well's response to pumping, well completion, and the type of geologic formation penetrated. Most of the theoretical models make assumptions that the aquifer is (1) of uniform thickness, (2) homogeneous and isotropic, and (3) all flow is horizontal. Single well tests also provide the specific capacity of the well. This is a measure of the productivity of a well, or the yield per unit of draw down.

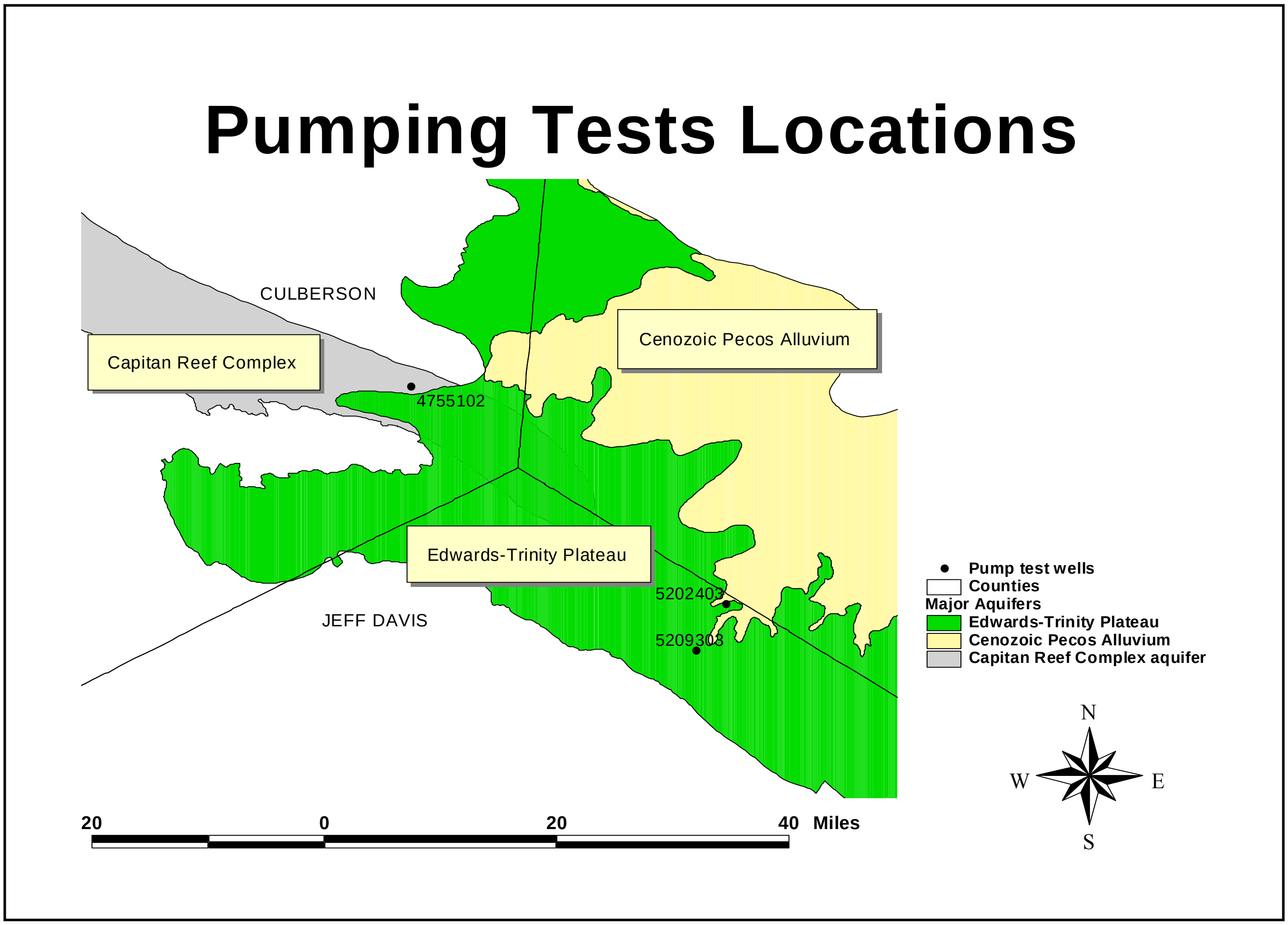


Figure 11.Pumping test locations.

On August 29, 2001, we conducted a short-term aquifer test on SWN 52-09-303, located on the Timber Mountain Ranch in Jeff Davis County (lat 30° 51" 27' N; long -103° 52" 52' W). According to our groundwater database, completion of this well is in the Cretaceous System. We maintained an average pumping rate of 7.5 gallons per minute (gpm) during the test. We used the software program AquiferWin32 to analyze the data using the Theis (Theis, 1935), Theis Recovery (Theis, 1935), and Cooper-Jacob (Cooper and Jacob, 1946) methods.

On September 5, 2001, the owner of one of the long-term monitoring wells conducted a short-term pumping test. The Huelster Well, SWN 52-02-403, is located south-southeast of Phantom Lake Spring in Jeff Davis County (Figure 1). According to our groundwater database, completion of this well is in alluvial terrace and channel deposits. While the interval between the data collecting transducer's monitoring event was insufficient for evaluating the pumping portion of the test, the slowness of the recovery did provide an estimation of transmissivity. We assumed a pumping rate of 500 gpm. We used the software program AquiferWin32 to analyze the data using the Theis Recovery (Theis, 1935) method.

On July 30, 2002, we conducted a short-term aquifer test on SWN 47-55-102, located on the Jobe Ranch in Culberson County (lat 31° 12" 47' N; long -104° 14" 09' W). The well is called "Section 22 south well" by the local rancher. According to our groundwater database, completion of this well is in the Cretaceous System. The pump for the system was shut off on July 29, 2002, at approximately 11:00 P.M. and the well was allowed to reach a static water level. We maintained a pumping rate of 19 gpm throughout the pumping phase of the test. We used the software program AquiferWin32 to analyze the data using the Theis Recovery (Theis, 1935), Neuman (Neuman, 1972), and Cooper-Jacob (Cooper and Jacob, 1946) methods.

We also compiled additional hydrologic properties from previous reports and studies.

2.2.5 Water Budget

In order to investigate impacts to spring discharge, it is important to understand the water budget of the groundwater system. This is simply the balance of water in and out of the system. The main component of water entering the system is from rainfall. Examples of other avenues of recharge to the system may be from cross-formational flow, losing streams (water seeping from the streambeds into the underlying formations), and return flow from irrigation. Water may exit the system through springs, gaining streams (water flowing into streambeds from the underlying formation), and pumping wells. A simple analogy is a full watering bucket with a leaky side. For example, if you experience an extended drought (you have not added any more water to the bucket), and groundwater pumpage practices remain the same or increase (you continue to use the watering bucket to water your plants), then discharge from springs may decrease or stop (the water falls to a level below the hole in the side of the bucket). Therefore, we investigated rainfall, pumpage, and spring discharge patterns to get a better estimate of the current and historical water balance of the system both locally and regionally.

2.2.5.1 Rainfall Collection

Our investigation of rainfall encompassed analyzing for historical trends and analyzing for responses to rainfall events at our continuous monitoring sites. For historical trends, we downloaded monthly precipitation data from information collected by the National Climate Data Center and compiled by Hydrosphere Data Products (2002). We selected three weather stations based on their proximity to the study area and length of record. The Mt. Locke weather station (ID 416104) is located in Jeff Davis County (lat 30.42° N; long -104.01° W) and has historical monthly precipitation totals from 1935 to 1999. The Balmorhea weather station (ID 410498) is located in Reeves County (lat 30.59° N; long -103.44° W) and has historical monthly precipitation totals from 1923 to 1999. The Van Horn weather station (ID 419295) is located in Culberson County (lat 31.02° N; long -104.50° W) and has historical monthly precipitation totals from 1939 to 1999. We used Microsoft Access and Microsoft Excel software to collate the information. We then plotted rainfall totals for comparison against pumpage and discharge data.

In addition to historical comparisons for our analysis of spring discharge responses to rainfall, we purchased two self-emptying tipping buckets with battery-operated dataloggers through Spectrum Technologies, Inc. We mounted the leveled tipping-bucket dataloggers on posts in locations where interference from vegetation or buildings would not influence the measurements (Figure 12). We initially set the dataloggers to record measurements every fifteen minutes to coincide with measurements recorded by the transducers. The dataloggers were capable of recording up to 7,000 measurements between downloads. Downloads required a laptop, SpecWare 5.0 software, and a download cable. We used Microsoft Access and Microsoft Excel software to collate the information. We then extracted and plotted the rainfall totals from April 2001 to June 2003 to compare against discharge data from the transducers.

Figure 12. Timber Mountain tipping bucket rain gage (on left) and TxDOT tipping bucket rain gage (on right).

Previous studies (LaFave and Sharp, 1987; Schuster, 1997; and Sharp and others, 1999) support that although the San Solomon Springs System is locally recharged by runoff from the Davis Mountains (resulting in the flow spikes) the base flow comes from a regional groundwater system. The source water to the springs is likely from the groundwater flowing through the Apache Mountains. In order to capture local recharge events by runoff from the Davis Mountains, we installed a tipping-bucket datalogger at Timber Mountain Ranch on April 26, 2001 (lat 30°52’24” N; long -103°55’04” W). This site is located generally to the south of Phantom Lake Spring between the springs and the Davis Mountains (Figure 1, Timber Mountain Rain gage).

In order to rule out rainfall events associated with the storm flow component to the spring system from the west, we installed a second tipping-bucket datalogger at the Interstate 10 and Interstate 20 (Figure 1, TXDOT rain gage) intersection on April 26, 2001 (lat 31°05’18” N; long -104°03’34 W). The site is located west-northwest of Phantom Lake Spring near the base of the Apache Mountains close to the Culberson, Reeves, and Jeff Davis county lines on Texas Department of Transportation (TxDOT) property.

2.2.5.2 Pumpage

We based our analysis of pumpage on data from our Water Use Survey database, which began collecting data in 1955. From 1955 to 1970, we inventoried only self-supplied groundwater use. Beginning with the 1971 survey, we expanded the survey to include self-supplied and purchased surface water. Water use may be reported either on a monthly or annual basis. About 85 percent of the surveys are completed and returned each year. Most municipal surveys that are not returned are estimated based on past data or information gathered from the Texas Commission on Environmental Quality (TCEQ). We send the survey to users in the following categories:

- municipal,
- manufacturing,
- mining, and
- steam-electric power.

The local county agricultural extension offices provided us with estimates of irrigation use. Livestock use was estimated from reported livestock populations by class and was assigned a per-head water use amount. The Livestock Reporting Service of the Texas Department of Agriculture provided us with reports on livestock populations. Irrigation and livestock estimates per county are available for 1974, 1977, 1980, and 1984 to the year 2000 in the Water Use Survey database. Additional data is available from TWDB Report 347, which began collecting irrigation data in 1958. There is very little information on pumpage from private domestic wells in the study area. The amount of pumpage from this category is estimated based on a methodology that uses the number of connections from the municipal survey, annual countywide population estimates, and average per capita usage estimates.

We used Microsoft Access and Microsoft Excel software to collate the information. We then plotted pumpage totals for comparison against rainfall and discharge data.

2.2.5.3 Spring Discharge

For historical trends and analysis, we based our investigation of spring discharge from information we obtained through the USGS. This entailed downloading information from their web site and supplementing this information with data contained in their annual USGS Water Resources Data for Texas publications and requesting copies of records from the USGS San Angelo office. We also explored current trends with the data we collected from our equipment and measurements we made during this project.

We used Microsoft Access and Microsoft Excel software to collate the information. We then plotted discharge totals for comparison against rainfall and pumpage data.

3.0 RESULTS

In the following subsections, we outlined the results of our research and analysis of data collected for this study. In the Section 4.0, we will outline the objectives listed in the original proposal and discuss the findings of our study. Section 5.0 contains our recommendations for future work and studies.

3.1 Spring and Groundwater Monitoring

To document changes in discharge to the springs in the San Solomon Springs System, we established long-term monitoring of water levels during Phase I and Phase II of this project.

3.1.1 Spring Monitoring

During this study, we monitored Phantom Lake, San Solomon, Giffin, and East Sandia springs. Discussions of the results of our monitoring are in the following subsections.

3.1.1.1 Phantom Lake Spring

We monitored pool levels inside Phantom Lake Spring for 795 days, from April 24, 2001, through June 26, 2003. Due to the volume of data points, totaling 28,053 records, we plotted the maximum and minimum daily water-level measurements for analysis (Figure 13). During this timeframe, the

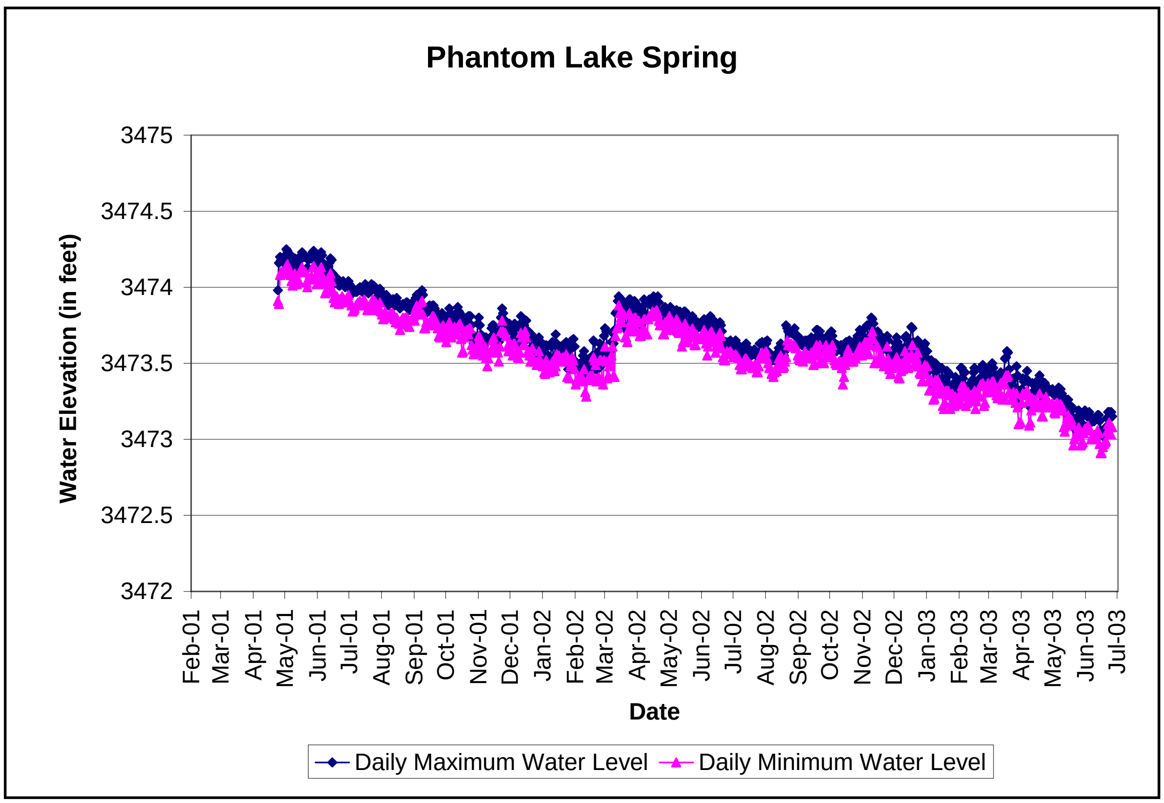


Figure 13. Phantom Lake Spring daily maximum and minimum transducer measurements.

maximum water-level elevation was 3474.25 feet above mean sea level (msl) on May 2, 2001. The minimum water-level elevation measured at 3472.91 feet above msl on June 15, 2003, and June 16, 2003. Water levels fell within a range of 1.34 feet with an average elevation of 3473.73 feet above msl.

In May 2001, the Bureau of Reclamation activated an emergency pumping system to move water from about 75 feet within the cave to the outside pool area. It was initially set to cycle 15 minutes on and 15 minutes off. The pump outflow raised the water level in the outside pool area about 0.75 feet and then naturally drained back through the check dam into the cave before the cycle repeated. This system was replaced in November 2002 with a constant, low-flow pump. Appendix A lists the measurements taken by U.S. Fish & Wildlife and TWDB of water levels in the outside pool at Phantom Lake Spring. The maximum water-level elevation was 3475.26 feet above msl on May 23, 2000, and the minimum water-level elevation measured at 3473.38 feet above msl on August 20, 2002, a difference of 1.88 feet (Figure 14).

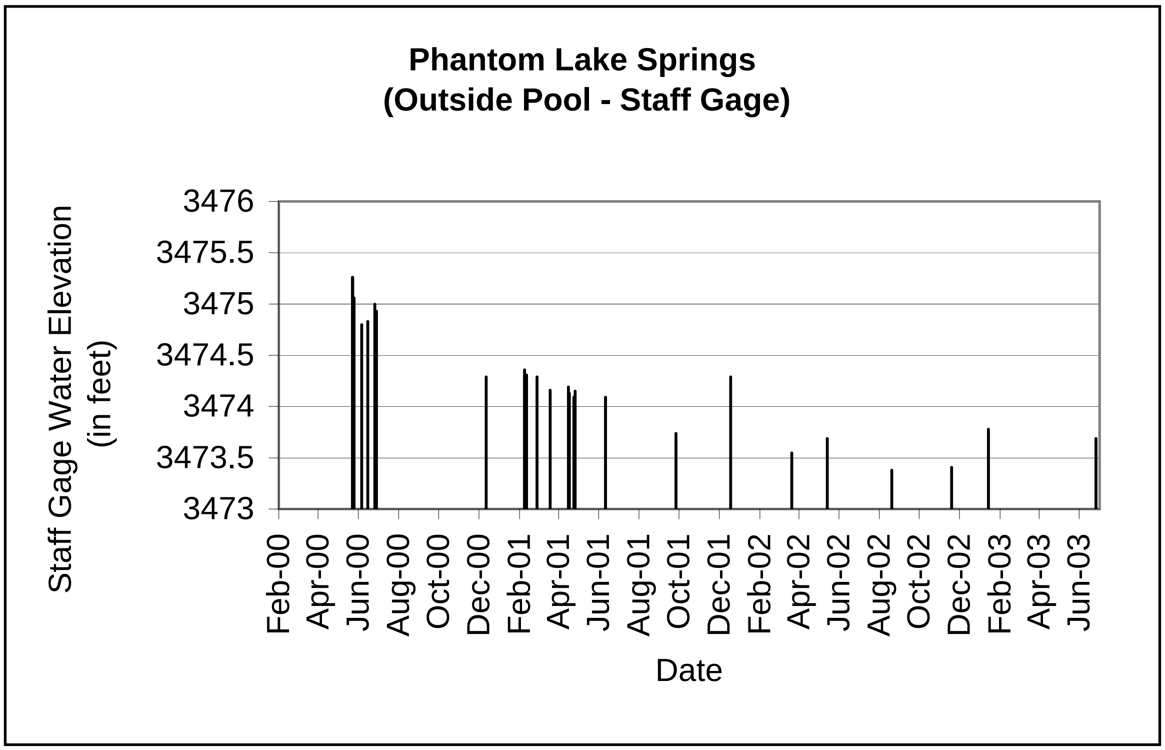


Figure 14. Graph of recorded water levels from the staff gage located in the outside pool at Phantom Lake Spring.

3.1.1.2 San Solomon Springs

We monitored San Solomon Springs for 387 days, from May 14, 2002, through June 26, 2003. Due to the volume of hourly measurements totaling 10,016 records, we plotted the maximum and minimum daily water-level measurements for analysis (Figure 15). The average daily array of measurements ranged within one to two inches. The water levels remained constant except for times when the gates were opened or the entire pool was drained for maintenance. We removed the transducer from January 14 through February 7, 2003, while the pool was emptied. The daily water levels in the pool at Balmorhea State Park remained relatively constant during our monitoring phase, partly due to the periodic release of water.

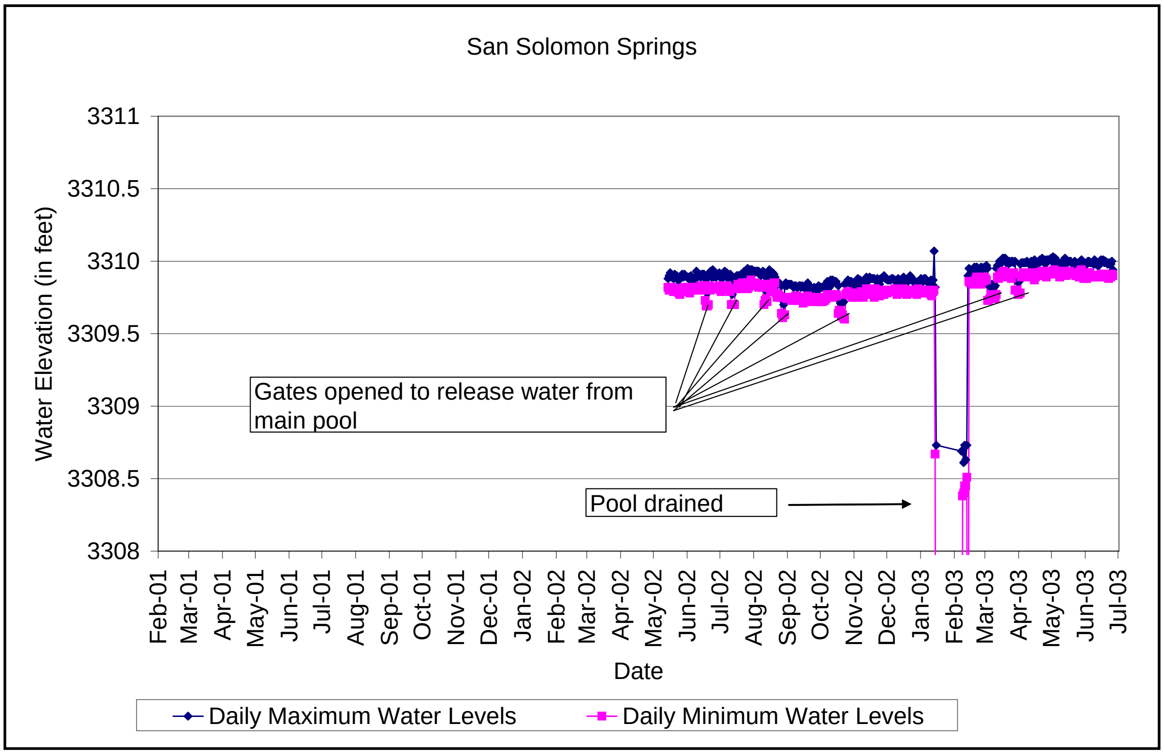


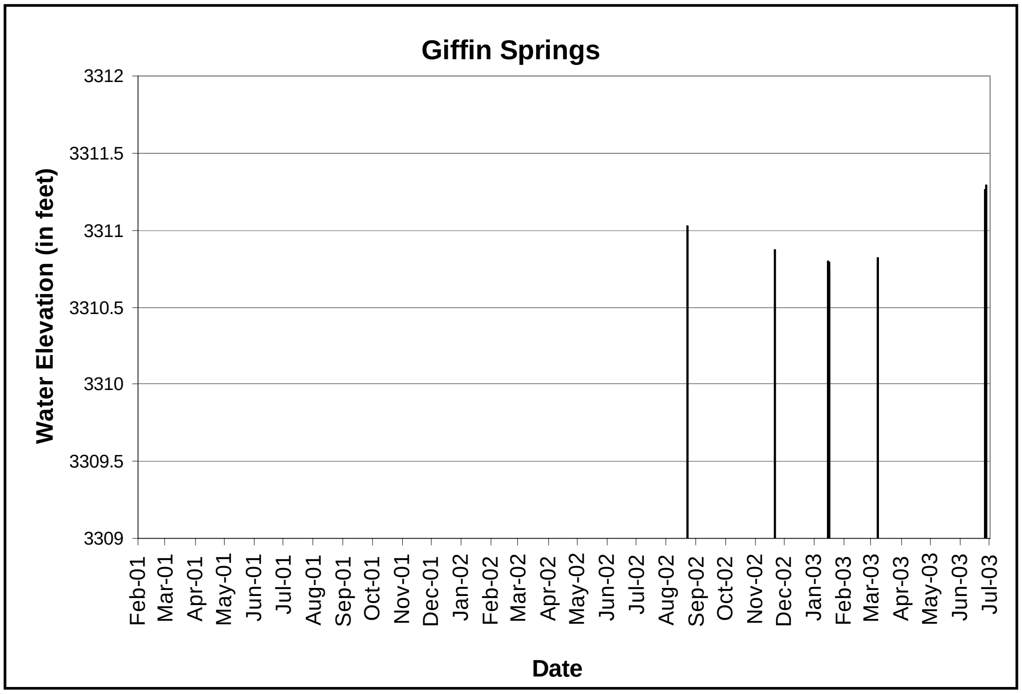
Figure 15. San Solomon Springs daily maximum and minimum transducer measurements.

3.1.1.3 Giffin Springs

We monitored Giffin Springs from August 21, 2002, through June 24, 2003. Staff gage readings peaked at 4.03 on June 26, 2003, and fell to a low of 3.48 on January 15, 2003 (Figure 16, top figure). We also downloaded provisional daily maximum/minimum stage data for Giffin Springs (August 1, 2002, through June 23, 2003) from the USGS Water Resources real-time surface water web page and graphed the results (Figure 16, bottom figure). Water levels remained relatively level within a 0.5-foot range.

3.1.1.4 East Sandia Springs

We monitored water levels in the wetland area of East Sandia Springs, with assistance from local staff at the Balmorhea State Park, from August 2002, through June 2003 (Figure 17). We recorded the lowest water level on August 20, 2002, at 2.37 feet. Water levels peaked in February and March 2003 to a height of 2.5 feet, a 0.23-foot increase.



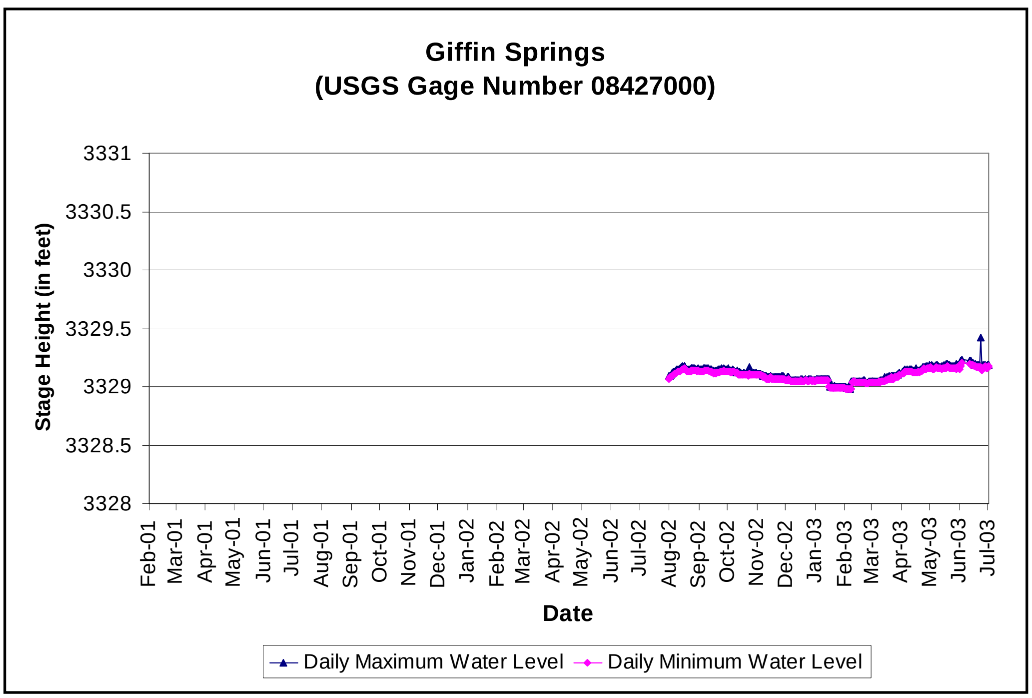


Figure 16. Giffin Springs field measurements of water stage heights in pool (top figure) and USGS provisional daily maximum and minimum stage height measurements for station 08427000 (bottom figure).

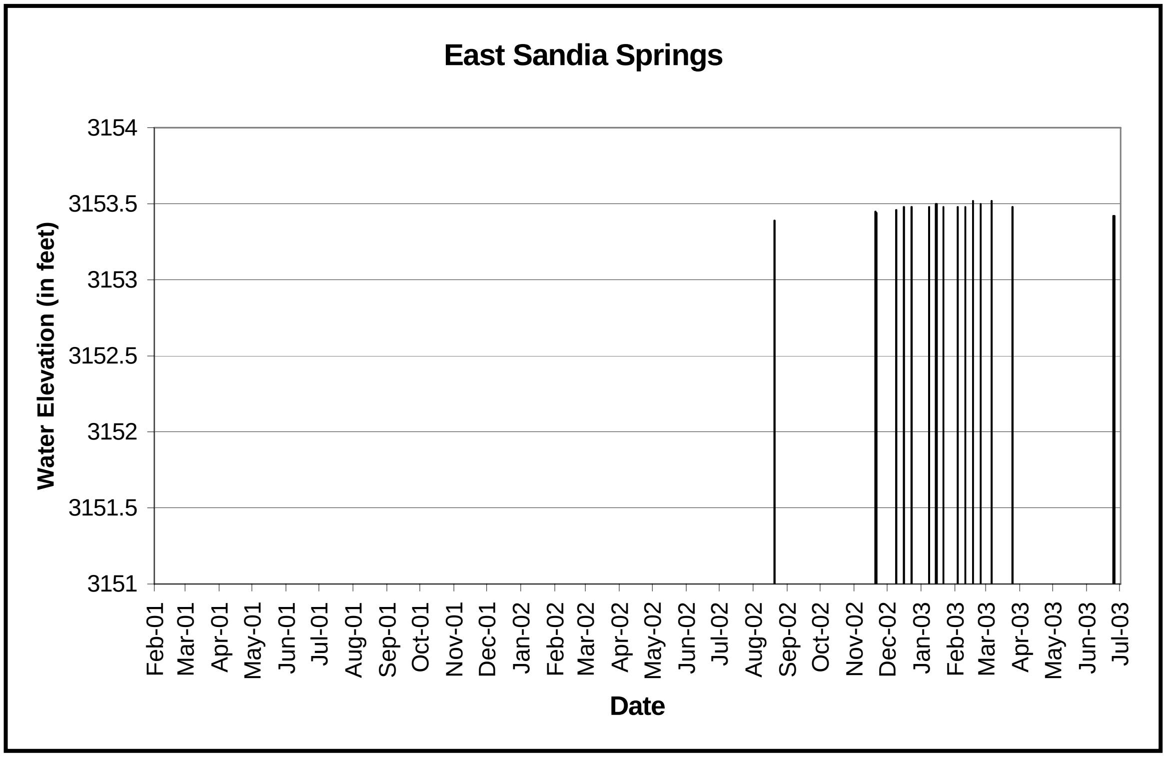


Figure 17. East Sandia Springs stage height staff gage measurements (in feet).

3.1.2 Groundwater monitoring

To determine possible effects of pumpage to discharge at Phantom Lake Spring, continuous monitoring of water levels at wells in the immediate vicinity of the spring was established during Phase I and Phase II of this project.

3.1.2.1 Hamilton Windmill (52-02-401)

We monitored the Hamilton windmill for 752 days, from February 6, 2001, through March 6, 2003. Due to the volume of data points, totaling 34,769 records, we plotted the maximum and minimum daily water-level measurements for analysis (Figure 18). The windmill supplied water for livestock and was in production frequently. The average recorded drawdown was approximately 6.5 feet. Maximum daily water levels dropped from 3483.75 feet in February 2001 to 3483.47 in March 2003, a difference of 0.28 feet or an average of 0.0112 feet of decline per month. The profile of the maximum daily measurements closely resembles Phantom Lake Spring (Figure 13). The November and December 2002, peaks substantiate that changes in groundwater flow influence both monitoring sites.

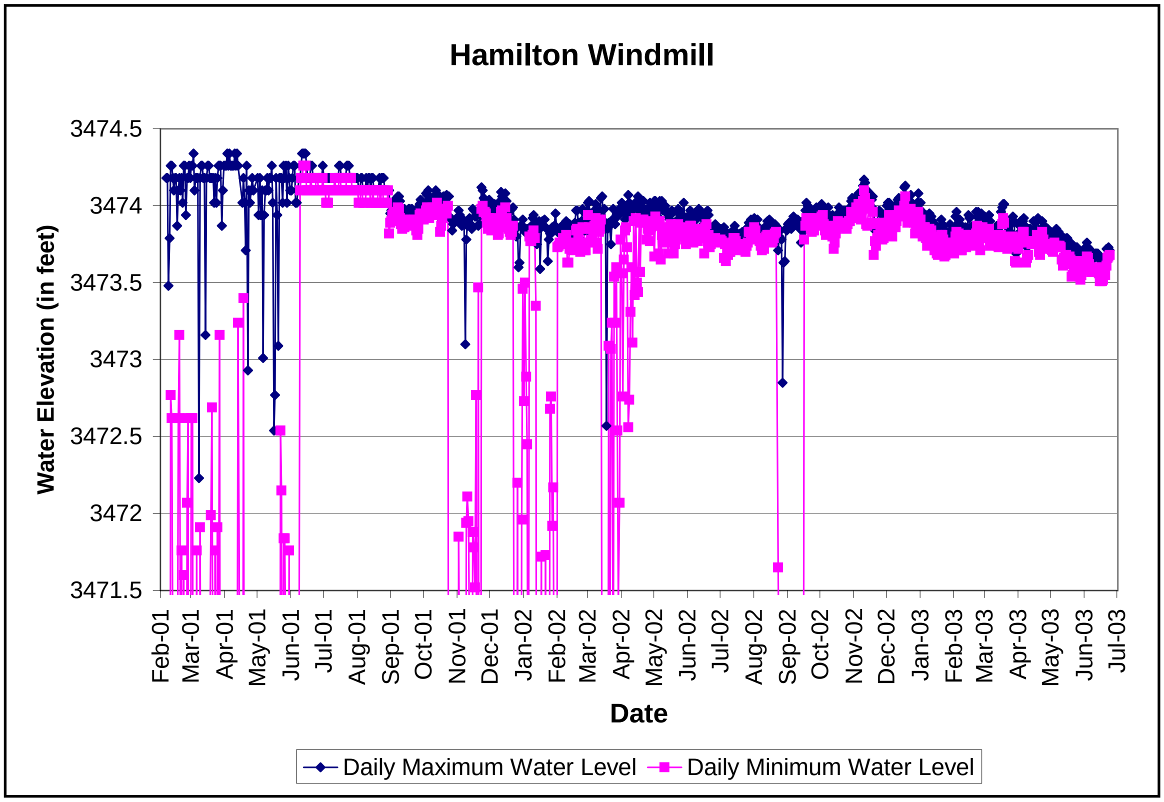


Figure 18. Daily maximum and minimum transducer measurements of Hamilton windmill monitoring site (in feet).

3.1.2.2 Huelster well (52-02-403)

We monitored the Huelster well for 681 days, from April 25, 2001, through March 6, 2003. Due to the volume of data points, totaling 28,007 records, we plotted the maximum and minimum daily water-level measurements for analysis (Figure 19). The well was a back-up source of water for the municipal wells located to the south and on occasion pumped by the owners. The average recorded drawdown was approximately 29 feet. Maximum daily water levels dropped from 3428.43 feet in April 2001 to 3424.63 in March 2003, a difference of 3.8 feet or an average of 0.17 feet of decline per month.

3.2 Potentiometric Surface Mapping

The development of potentiometric surface maps allows you to analyze probable groundwater flow paths. The following subsections discuss the results of the water-level maps developed around the discharge area and regionally.

3.2.1 Local Maps

In Open File Report 97-03, TWDB developed a water level map for the area in the immediate vicinity of the springs (Ashworth and others, 1997). We developed a similar map by extracting the same 1997 measurements from our groundwater database (Figure 20). Groundwater flow is predominately from the southwest to the northeast, paralleling the topographic dip. A cone of depression reflects heavy

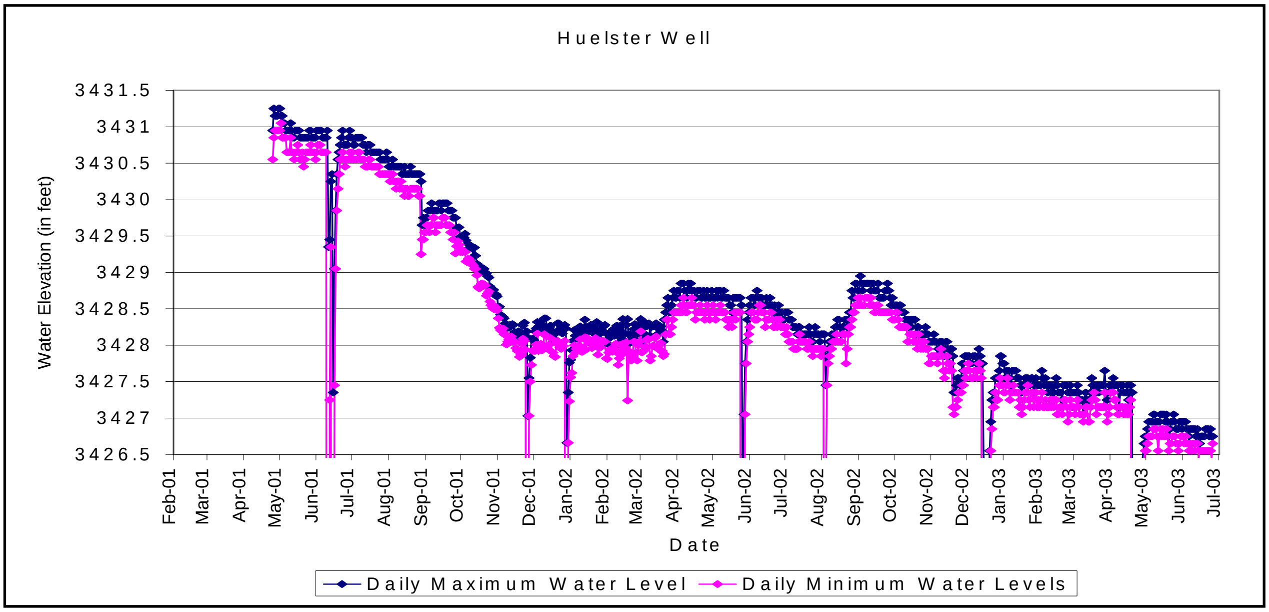


Figure 19. Graph of maximum and minimum daily recordings from the transducer at the Huelster well monitoring site.

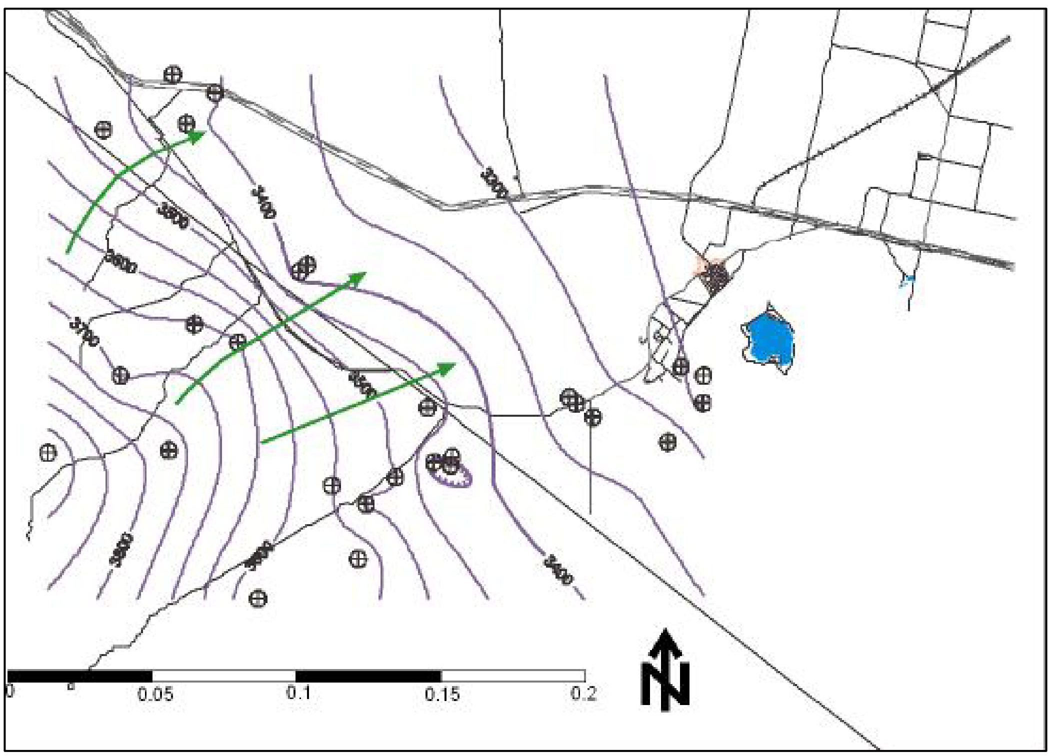


Figure 20. Potentiometric surface map from data collected around the San Solomon Springs System in 1997. Arrows indicate probable groundwater flow paths from the southwest to northeast (Modified from Ashworth and others, 1997). Contour interval is 50 feet.

pumpage in the municipal complex to the south of Phantom Lake Spring in Jeff Davis County. Further research of the groundwater database indicated the wells had recently been pumped. Therefore, the cone of depression may have reflected the residual draw down of the wells as they recovered to static water levels.

In February 2001, we re-measured many of the same wells in Jeff Davis and Reeves counties. The purpose was to establish current conditions and to uncover possible changes in water levels in the intervening years (Figure 21). Comparison of figures 20 and 21 shows groundwater flow is still from the southwest to the northeast and that no significant change in local water levels has occurred. The cone of depression at the municipal pumping complex located to the south of Phantom Lake Spring in Jeff Davis County is gone.

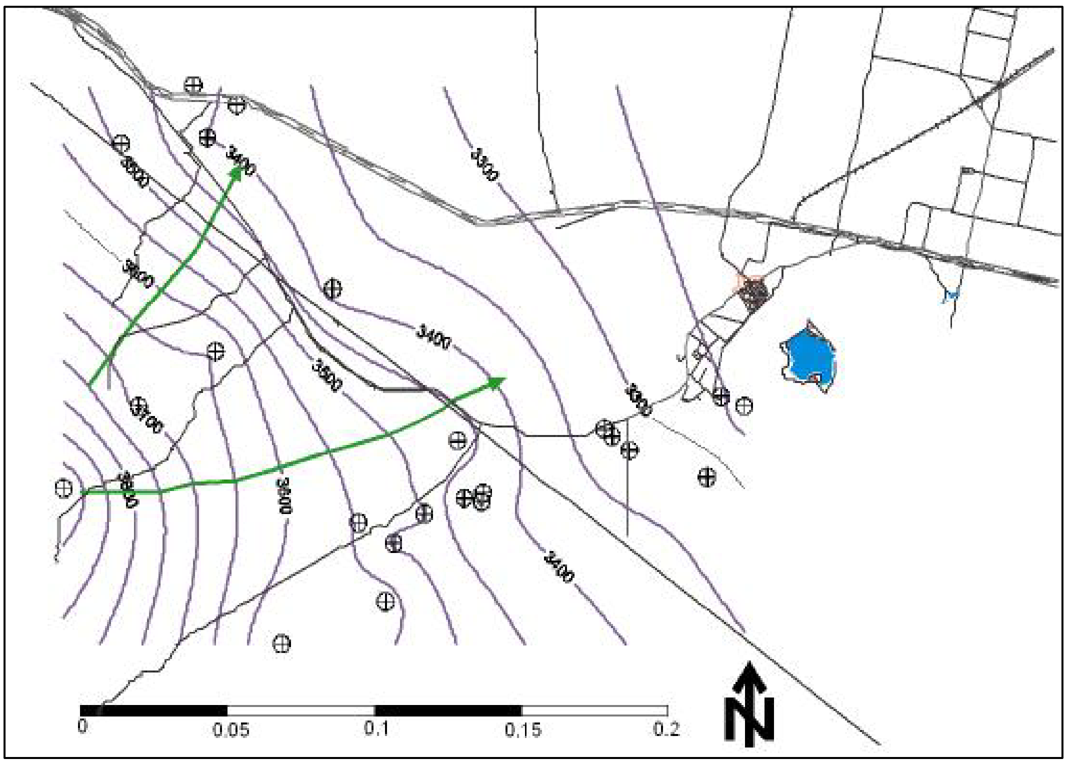


Figure 21. Potentiometric surface map from data collected around the San Solomon Springs System in 2001. The arrows indicate probable groundwater flow path is still from the southwest to northeast. Contour interval is 50 feet.

3.2.2 Water Levels and Regional Groundwater Flow

Nielson and Sharp (1985) identified the presence of two groundwater divides in the Salt Basin based on water-level measurements from the 1950s and 1960s. The northern divide follows along the Babb flexure zone and the central divide along the Victorio (Bitterwell Break) flexure zone (Goetz, 1980). The basin and range topography of the study area causes recharge from the alluvial fans on the mountain slopes to flow towards the valley floor in the center of the closed basins. Thus, groundwater flow was preferentially directed towards the center of the salt flats in the north and the central areas of the Salt Basin. However, in the southern part of the Salt Basin near Wild Horse Flats, groundwater flow was from the Bolsons towards the Apache Mountains in the east. Nielson and Sharp (1985) reported that groundwater flow was impeded east due to the presence of low permeability sediments of the

Delaware Mountain Group and flow westwards was prevented due to low fracture porosity of the Diablo platform.

We reviewed water level information from the TWDB groundwater database and developed:

- a water-level map for the pre-development condition using water-level measurements from 1930 to 1960 (Figure 22), and
- a water level map using water-level measurements from 1930 to 2003 (Figure 23).

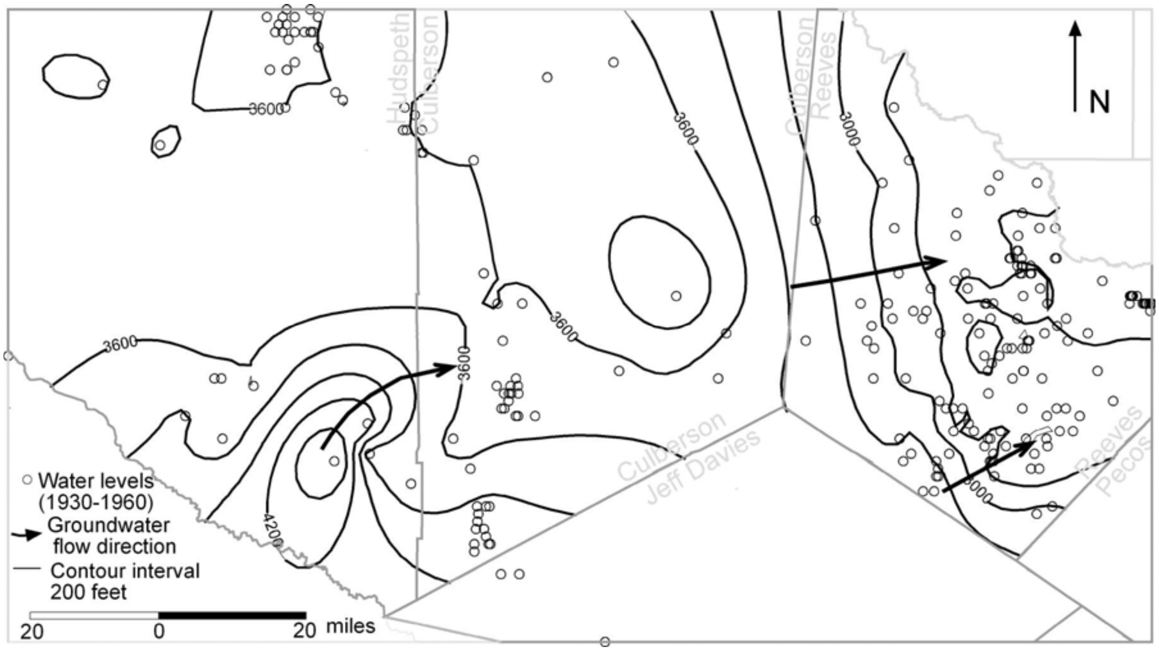


Figure 22. Water-level elevation map using pre-development groundwater elevation. Measurements from the TWDB groundwater database (includes 1930 to 1960 measurements). Water-level map shows a general west to east groundwater flow direction with some radial flow around topographic highs. We used 200-foot water-level intervals. Water-level contours were developed using the point kriging option in Surfer where values are estimated at the grid nodes. Contours are accurate where there are adequate control points.

We included only winter water-level measurements in developing the water-level maps when the water levels presumably were less affected by pumping. When developing the water-level maps we used the earliest measurement if there were multiple water-level measurements from the same well.

The pre-development water level map constructed was based on limited data but was surprisingly similar to the water-level map constructed for 1930 to 2003. From our examination of the water-level maps, we have not observed distinct groundwater divides as observed by Nielson and Sharp (1985).This may be because the gradient that defines the divides may be subtle and subject to change direction.

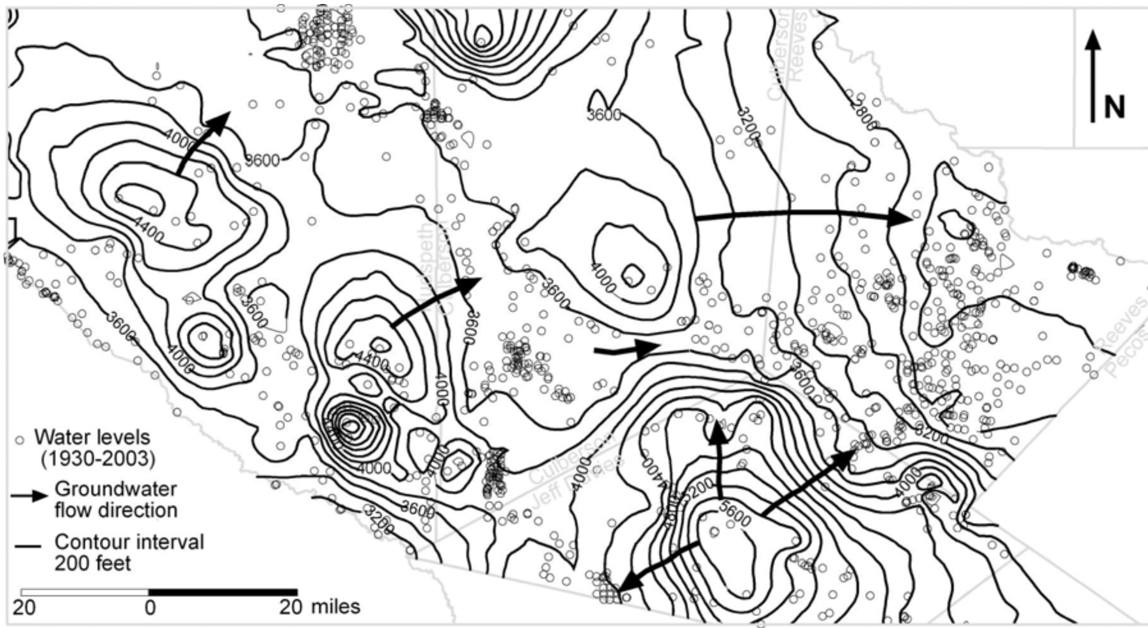


Figure 23. Water-level elevation map using groundwater elevation measurements from the TWDB groundwater database (includes 1930 to 2003 measurements). Water-level map shows a general west to east groundwater flow direction with radial flow directed from the topographic highs. We used 200-foot water-level intervals. Water-level contours were developed using the point kriging option in Surfer where values are estimated at the grid nodes. Contours are accurate where there are adequate control points.

3.2.3 Global Positioning System Surveys

Utilizing the GPS base station approach with a known elevation point provided a relatively accurate elevation difference between the points collected with the rover unit during the survey. Using the NGS benchmark as the known elevation point of 3471.72 feet, the elevation of the USGS benchmark at Phantom Lake Spring was determined to be 3476.26 feet and the elevation of the new benchmark at Phantom Lake Spring is 3478.50 feet (see Table 2).

Table 2.Elevation, latitude, and longitude of benchmarks and well monitoring sites collected. Latitude and Longitude expressed in decimal degrees.

Site	North Latitude	West Longitude	Elevation (feet)	Accuracy (feet)	Date Surveyed
NGS benchmark along highway 290	30.941609	-103.843699	3471.72	0.105	3/20/02
USGS gage benchmark at Phantom Lake Spring	30.934649	-103.848182	3476.26	0.082	3/20/02
New benchmark at Phantom Lake Spring	30.934894	-103.849605	3478.50	0.075	3/20/02
Hamilton Windmill	30.935253	-103.853887	3548.43	1.903	6/24/03
Huelster Monitoring well	30.920205	-103.843775	3500.82	2.067	6/24/03

On March 20, 2002, we set up a surveyor's level at the USGS benchmark and took measurements to the "new benchmark" to verify the GPS elevation readings. The surveyor's level was then set-up at the new benchmark and we took measurements to the USGS benchmark. The results utilizing the surveyor's level were within a quarter of an inch difference than those collected with the GPS units. Therefore, the GPS figures appear reasonable and accurate.

In order to correlate staff gage reading with actual elevations and to approximate the water levels collected by the transducer installed within Phantom Lake Spring, we gathered additional elevation measurements during the survey. We show the elevations for each of these points in Table 3.

Table 3. Surveyed staff gage elevations and Phantom Lake Spring gate elevation. We used the gate elevation to spatially tie-in the cave survey (Tucker, 1996) to topography. *The "zero reading" elevation of the staff gage is so field personnel can take the water-level reading and add it to the elevation listed to get the current water surface elevation.

Phantom Lake Spring Site	Elevation (feet)
Zero reading on outside staff gage*	3469.81
Zero reading on inside staff gage	3469.49
Middle bottom of gate to spring	3475.61
Zero reading on gage in field*	3474.06

Using a benchmark identified as BSP1 (lat 30.944533 N; long –103.788739 W) located in Balmorhea State Park as the known elevation point of 3318.63 feet, we surveyed water levels at San Solomon, Giffin, and East Sandia springs on June 25,2003. At each of the springs a temporary benchmark was established (Table 4).

Table 4. Temporary benchmark locations and their descriptions from June 25, 2003 GPS spring survey. Latitude and Longitude expressed in decimal degrees.

Temporary Benchmark Site	North Latitude	West Longitude	Elevation (feet)	Accuracy (feet)	Benchmark Description
San Solomon	30.944666	-103.787732	3311.02	0.492	Existing iron pin located in the Northeast corner of south outlet leading to cienga
Giffin	30.945089	-103.791133	3311.83	0.427	Steel pin located in a cement structure on the north side of the spring
East Sandia	30.940827	-103.728797	3156.75	2.625	Concrete monument on the south side of the spring 790' from the centerline of US 290

In order to correlate staff gage readings with actual elevations, we collected additional elevation measurements during the June 25, 2003 survey. Elevations for each of these points are shown in Table 5.

Table 5. Elevation of staff gages at Giffin and East Sandia Springs. *The "zero reading" elevation of the staff gage is so field personnel can take the water-level reading and add it to the elevation listed to get the current water surface elevation.

Spring Site	Elevation (feet)
Zero reading on Giffin staff gage*	3307.26
Zero reading on East Sandia staff gage*	3151.02

In addition, we located six springs in the San Solomon Springs pool at Balmorhea State Park and surveyed the elevation of their discharge points (Figure 24). We also documented depth readings in Giffin Springs pool.

3.2.4 Phantom Lake Spring

Since Phantom Lake Spring has undergone the most substantial change in discharge in recent years, a better understanding of its internal system was considered essential to this study. Bill Tucker, a cave diver, has been surveying and documenting the underground passageways associated with the Phantom Lake Spring cave system since the mid 1990s (Tucker, 1996, 1999, and 2000). Using his survey information, we developed a 2-dimensional portrayal of the cave with ArcGIS 3-D spatial analyst. We tied the cave survey to topography by using the surveyed elevation of the gate at Phantom Lake Spring (Table 3) where Bill Tucker started his cave survey. Digital Elevation Model (DEM) coverage was correlated to the same coordinate and draped over the surface (Figure 25). Note, the passageways and chambers that comprise the Phantom Lake cave system were portrayed with simplified pipe segments and do not represent actual cave dimensions. The results of this analysis clearly show that the entrance to the cave system is also the highest point in the network of passageways. For groundwater to discharge to the surface, the cave system must be fully saturated.

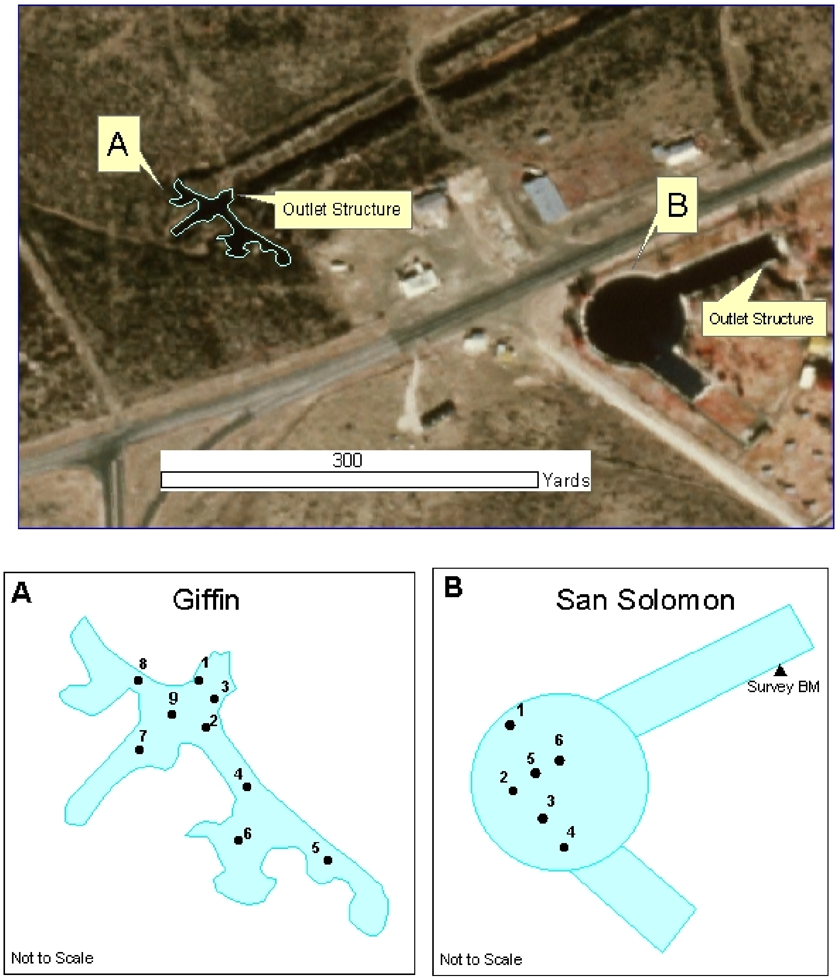
We then added 1997 and 2001 groundwater-level surface layers to the program to see the relationship to the cave system (Figure 26). Within this period, water levels dropped from the middle of the cave entrance, to a point near the base of the cave entrance. So even though water fills most of the passageways, water no longer flows out of the cave.

3.3 Geochemistry

Water quality modeling information can be used to help delineate flow paths of the spring system, determine any effects that local rainfall may have on discharge, possibly explain the processes that lead to the decline in discharge to Phantom Lake Spring, and assist in suggesting the location of existing wells for regional monitoring within the aquifers that are source waters to Phantom Lake Spring.

3.3.1 Field measurements

Detailed water quality field measurements including pH, conductivity, and temperature are listed in Appendix A. The following sections discuss the relationships and trends observed.



	Water Depth	Elevation
1 Staff Gage	4'	3,307.26'
2	5.39'	3,305.87'
3	4.32'	3,306.94'
4	3.00'	3,308.26'
5	4.04'	3,307.26'
6	3.02'	3,308.24'
7	3.81'	3,307.45'
8	3.40'	3,307.86'
9	4.62'	3,306.64'

N

	Water Depth	Elevation
Spring 1	6.44'	3,303.52'
Spring 2	19.74'	3,290.22'
Spring 3	19.76'	3,290.20'
Spring 4	11.76'	3,298.20'
Spring 5	22.08'	3,287.88'
Spring 6	10.19'	3,299.10'

Figure 24. Approximate location of depth measurements in Giffin Springs (insert A) and surveyed elevations of springs at San Solomon pool in Balmorhea State Park (insert B). The water elevation at San Solomon was 3,309.96 feet above mean sea level and the water elevation Giffin Springs was 3,311.26 feet above mean sea level when we recorded the depth readings.

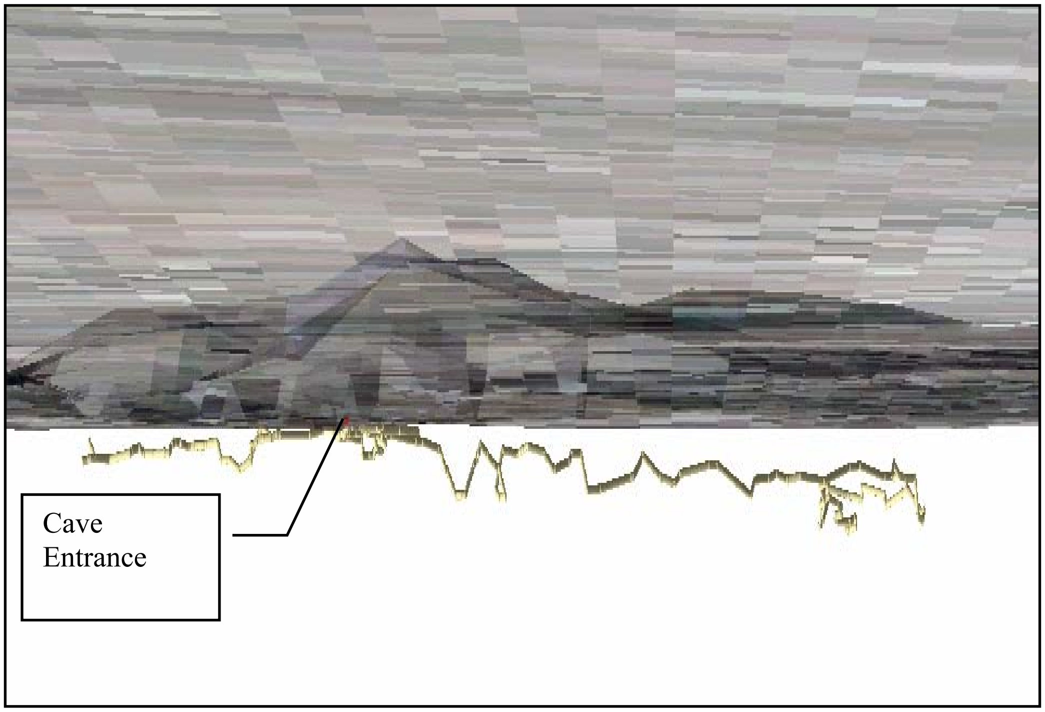


Figure 25. Results of combining cave survey (Tucker, 2000) to surface topography using ArcGIS 3-D analyst. Davis Mountains are in the background. The longer passageway tracks in a northwest direction. Note: the vertical scale has been exaggerated to more clearly show the relationship of the cave entrance and passageways. This view is from the subsurface.

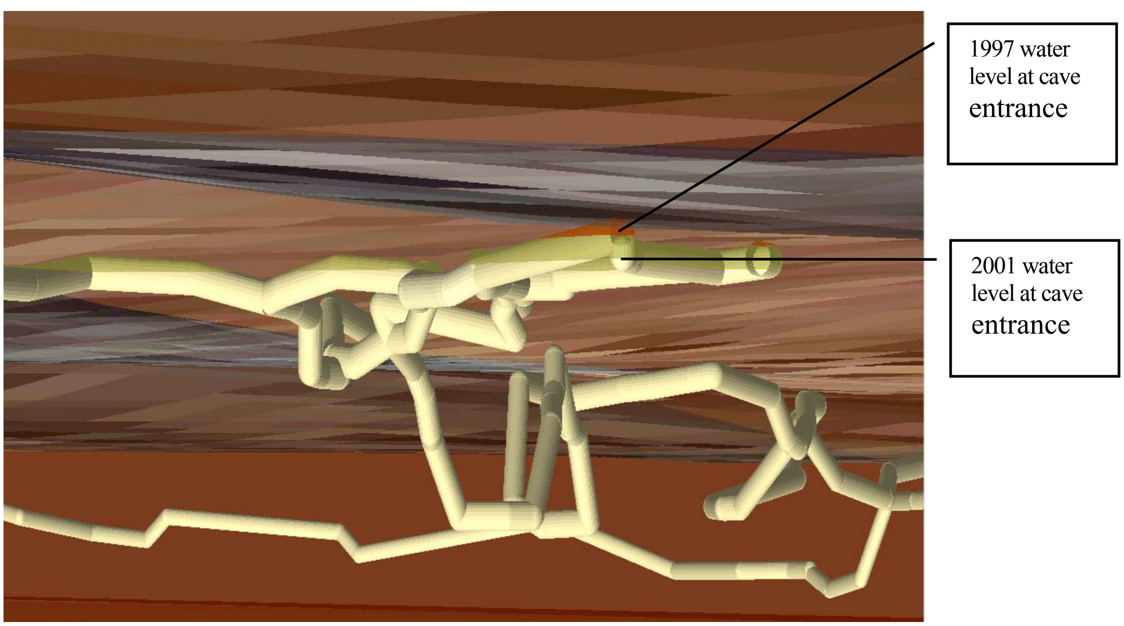


Figure 26. 1997 and 2001 water levels layers added to a 3-dimensional representation of the Phantom Lake Spring system. View is from the subsurface looking upwards to land surface. Vertical scale exaggerated.

3.3.1.1 pH

pH is defined as the negative logarithm of the concentration of hydronium ions in a solution (Robinson and others, 1992). Basically pH is the measurement of how acidic or basic water is; values greater than 7 indicates a base and values less than 7 indicates an acid. Seawater has a pH around 8.5, pure water is 7.0, precipitation normally falls between 5 and 6.5, and normal stream flows range between 6 and 8 (USGS, 2003). Changes in pH are almost as important as the actual measured value. For example, a lowering of pH may indicate rainfall mixing with groundwater. For comparison, we plotted the measured values of pH for Giffin, East Sandia, San Solomon, and Phantom Lake Spring (Figure 27).

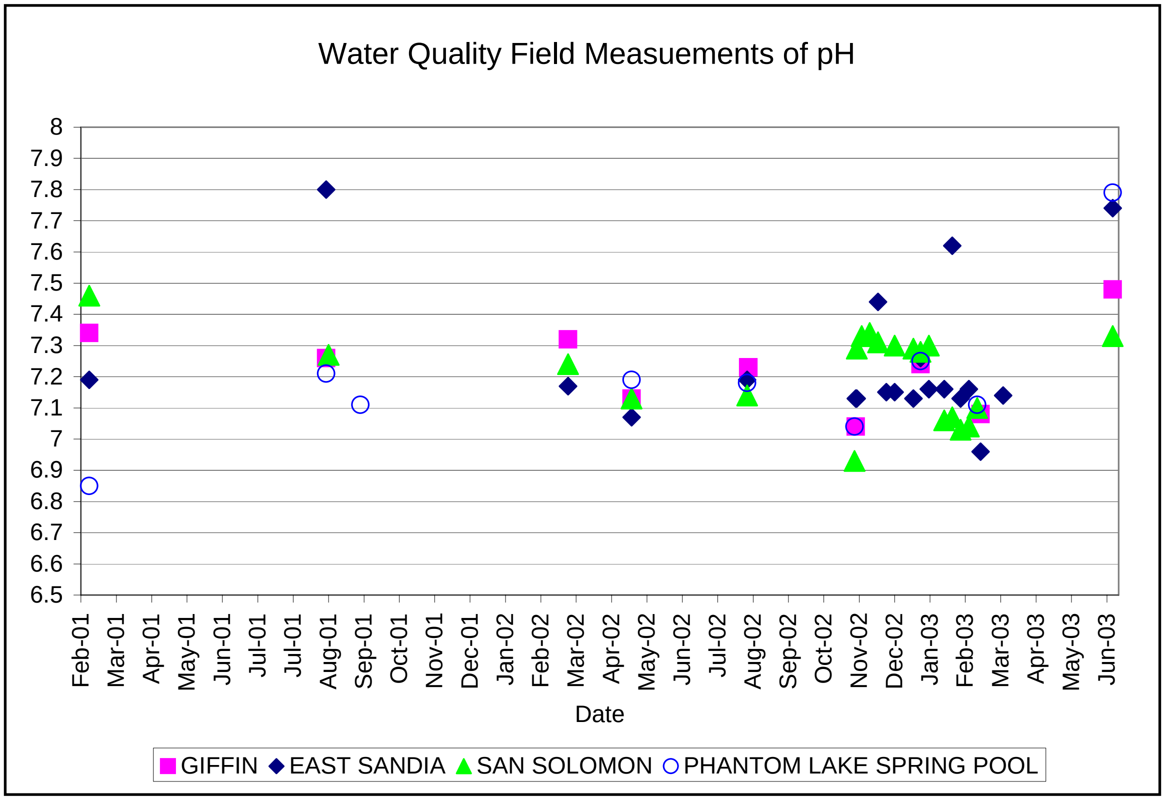


Figure 27. Water quality measurements of pH collected using calibrated field equipment.

The average pH measurement for all four springs was 7.2. The lowest pH measured at each spring was 6.85 (Phantom Lake Spring on February 8, 2001), 6.93 (San Solomon Springs on November 19, 2002), 6.96 (East Sandia Springs on March 6, 2003), and 7.04 (Giffin Springs on November 20, 2002). The highest pH measured at each spring was 7.46 (San Solomon Springs at February 8, 2001), 7.48 (Giffin Springs on June 26, 2003), 7.79 (Phantom Lake Spring on June 26, 2003), and 7.8 (East Sandia on August 28, 2001).

3.3.1.2 Conductivity

Specific conductance is a measure of water's ability to conduct an electrical current. Pure water has a very low specific conductance and seawater has a high specific conductance. Rainwater often reacts with airborne dust, pollen, and gasses and often has a higher specific conductance than pure, distilled water (USGS, 2003). For comparison, we plotted the measured values of conductivity for Giffin Springs, East Sandia Springs, San Solomon Springs, and Phantom Lake Spring (Figure 28).

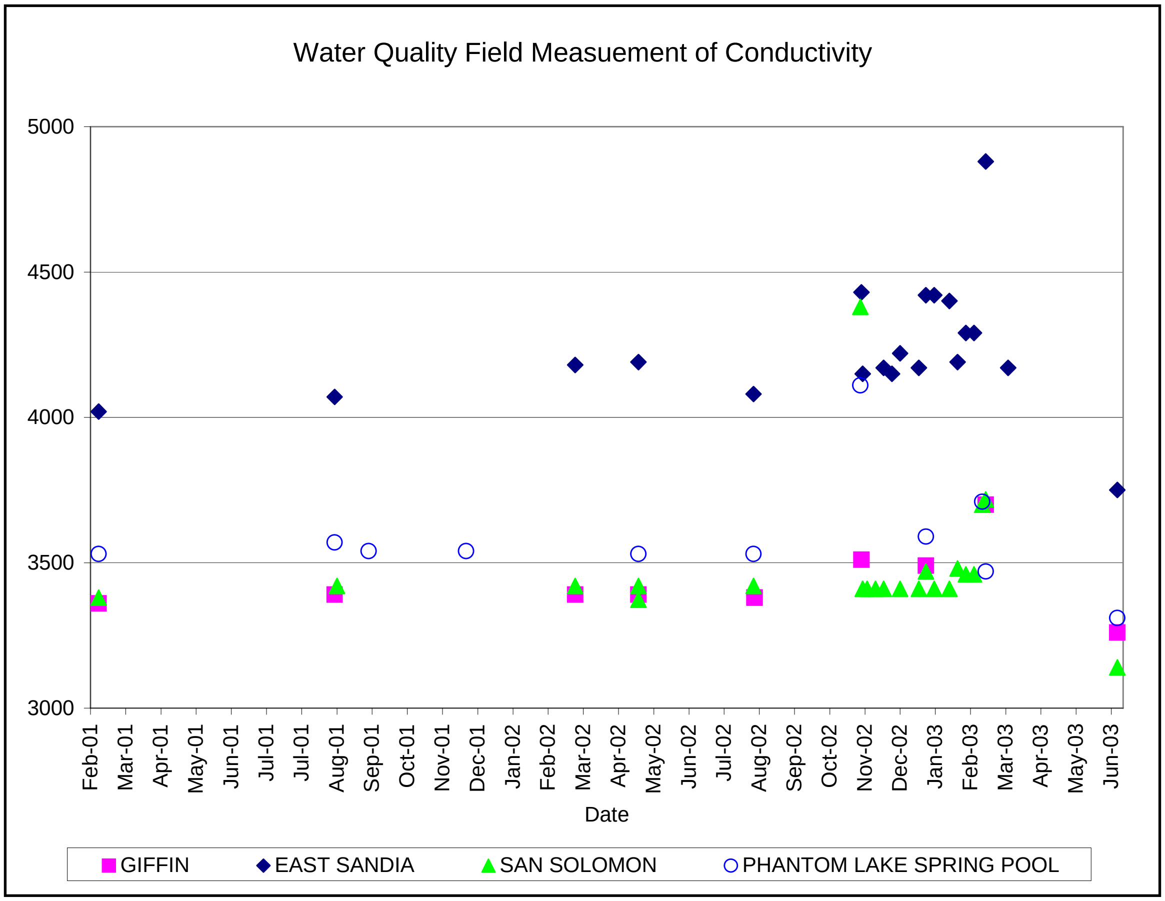


Figure 28. Water quality measurements of conductivity collected using calibrated field equipment. Specific conductance is reported in micro-Siemens.

The average field measured specific conductance varied per spring: Giffin Springs averaged 3,425 micro-Siemens (µS); San Solomon Springs averaged 3,478 µS; Phantom Lake Spring averaged 3,585 µS; and East Sandia Springs averaged 4,232 µS. East Sandia Springs consistently measured a higher specific conductance than the other three springs. The lowest field measured specific conductance for each of the springs occurred on June 26, 2003: Phantom Lake Spring measured 3,310 µS; San Solomon Springs measured 3,140 µS; East Sandia Springs measured 3,750 µS; and Giffin Springs measured 3,260 µS. The highest specific conductance measured at each spring was 3,700 µS on March 6, 2003, at Giffin Springs; 4,880 µS on March 6, 2003, at East Sandia Springs; 4,110 µS on November 19, 2002, at Phantom Lake Spring; and 4,380 µS on November 19, 2002, at San Solomon Springs.

3.3.1.3 Temperature

For comparison, we plotted the measured values of temperature for Giffin Springs, East Sandia Springs, San Solomon Springs, and Phantom Lake Spring (Figure 29). As expected, high water temperatures occurred in the summer with lows in winter.

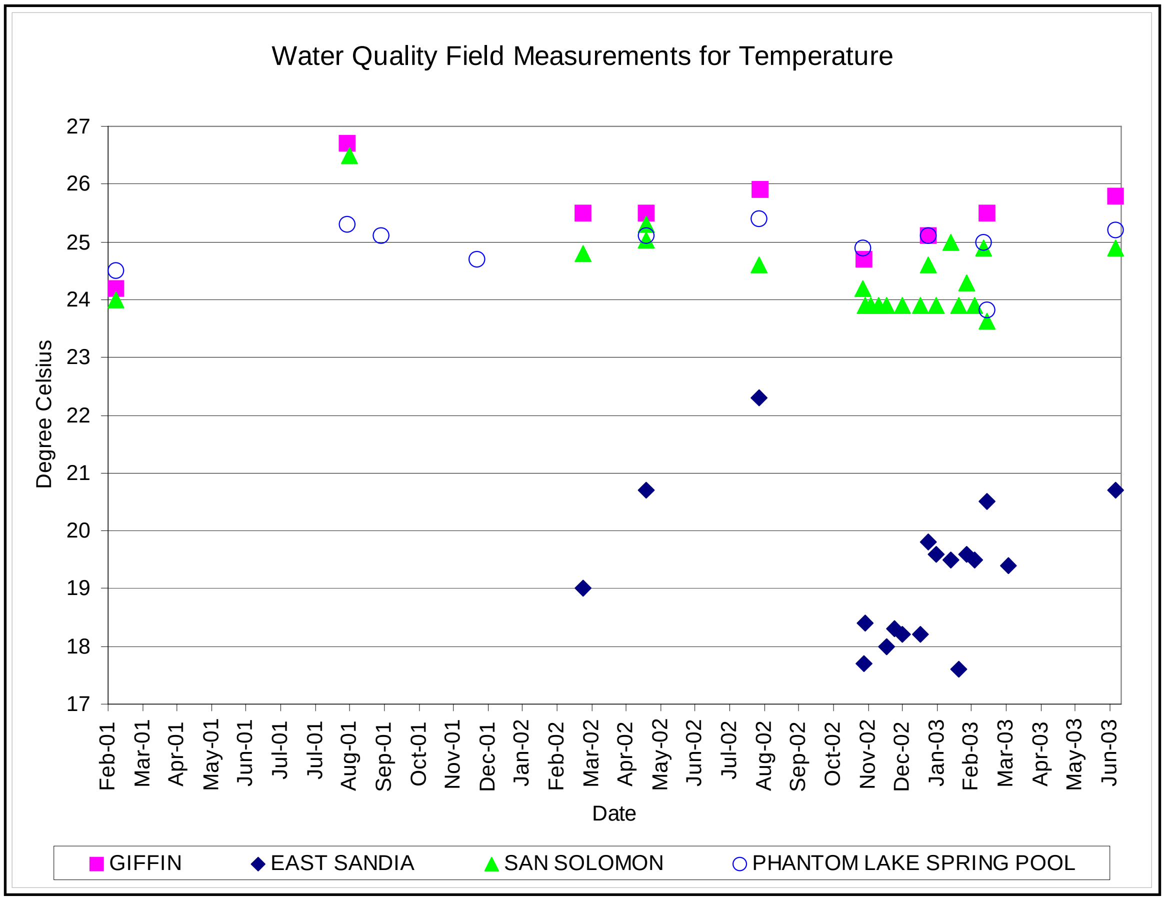


Figure 29. Water quality measurements of temperature collected using field equipment.

East Sandia Springs had the lowest average temperature of 19.31°C with a high temperature of 22.3°C (August 20, 2002) and a low temperature of 17.6°C (February 10, 2003). San Solomon Springs average water temperature was 24.4 °C with a high temperature of 26.5°C (August 30, 2001) and a low temperature of 23.63°C (March 6, 2003). Giffin Springs average water temperature was 25.5 °C with a high temperature of 26.7°C (August 28, 2001) and a low temperature of 24.2°C (February 8, 2001). Phantom Lake Spring average water temperature in the pool was 24.9 °C with a high temperature of 25.4°C (August 20, 2002) and a low temperature of 23.83°C (March 6, 2003).

3.3.2 Transducer Water Quality

We continuously monitored conductivity and temperature parameters with the transducer equipment installed at Phantom Lake Spring, San Solomon Springs, Hamilton Windmill, and the Huelster well.

The following sections discuss the relationships and trends observed.

3.3.2.1 Conductivity

When average daily conductivity measurements are plotted the Huelster monitoring well plots substantially below the other three monitoring sites (Figure 30). The Huelster well monitoring site average specific conductance was 0.50 micro Siemens per centimeter (μS/cm) with a median value of 0.48 μS/cm, suggesting a fresher source of water. The daily variance spikes for the Huelster well coincide with periods when the pump was activated. For example, the lowest daily average reading occurred on April 20, 2003 (0.45 μS/cm) on a day when the pump was turned on and fresh water entered the wellhead. The highest average daily reading, 1.17 μS/cm, occurred several days later on April 23, 2003 when the well was recovering and sediment within the borehole was probably in suspension.

The Hamilton windmill appeared to be the most responsive to changes in conductivity. There appears to be a correlation to changes in conductivity to when the windmill pump was activated (Figure 18). In addition, the daily variance and peaks in conductivity (Figure 30) appear to relate to peaks observed in water levels (Figure 18). For example, daily variance for conductivity spikes on November 10, 2002; December 17, 2002; and December 30, 2002 and water levels spike on November 10, 2002; December 18, 2002; and December 30, 2002. Appendix A (Figure A) shows a detailed comparison of rainfall, conductivity, temperature, and water levels for this period. This suggests a surge of water enters the system, water levels increase, sediments are stirred into suspension, and conductivity readings increase. The average specific conductance for the Hamilton windmill site was 3.37 μS/cm with a median value of 3.36 μS/cm. The lowest daily average reading occurred on February 1, 2002 (2.69 μS/cm). The highest daily average reading occurred September 1, 2002 (4.24 μS/cm).

San Solomon Springs remained relatively constant with an average daily conductance reading of 3.71 μS/cm with a median value of 3.71 μS/cm.

Phantom Lake Spring specific conductance was deemed unreliable. However, after we installed the new transducer on August 20, 2002 the transducer maintained a daily average conductance of 3.52 μS/cm, which appeared reasonable when compared to San Solomon and the Hamilton windmill monitoring sites.

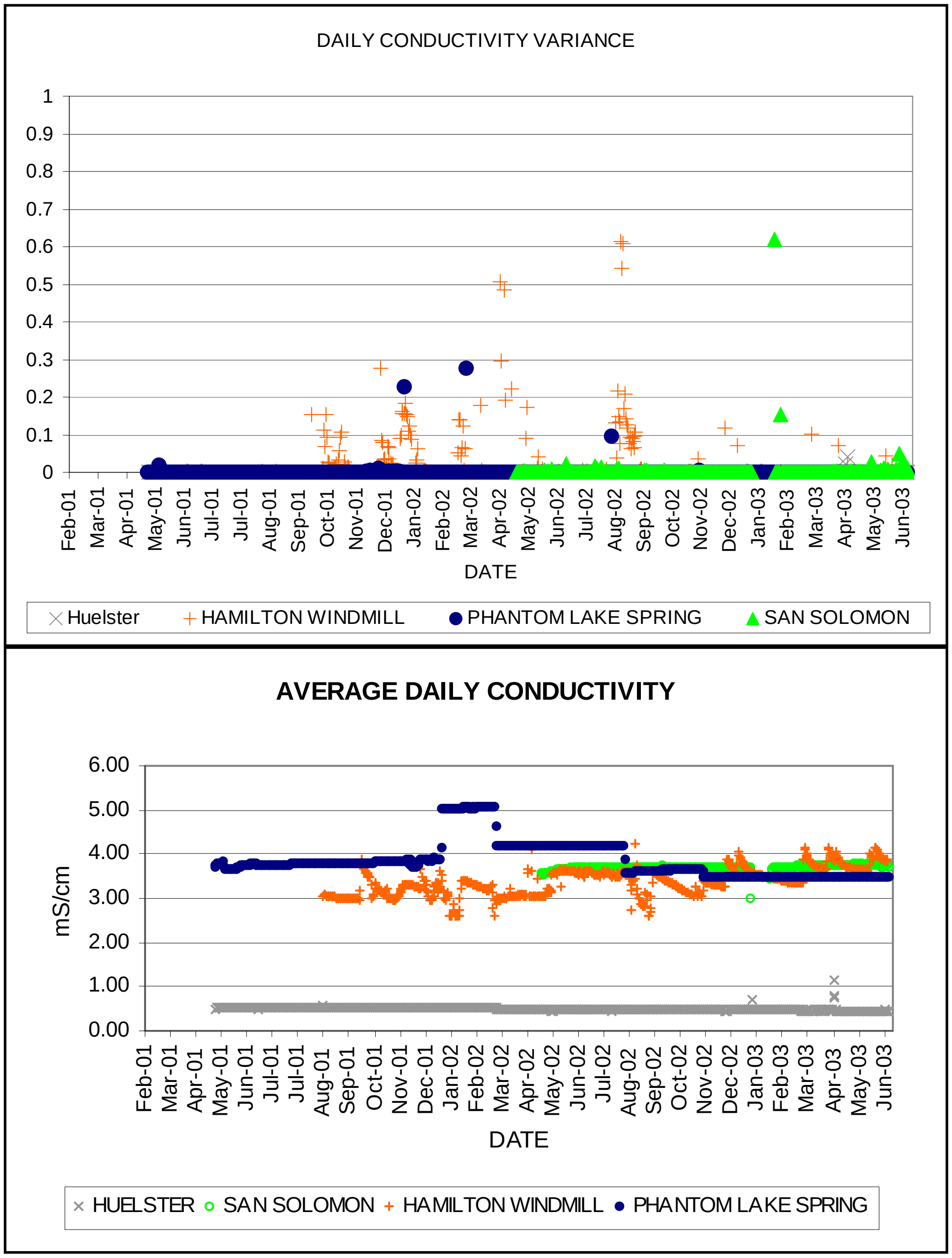


Figure 30. Top figure shows daily variances of transducer conductivity measurements for Huelster, San Solomon Springs, Hamilton Windmill, and Phantom Lake Spring monitoring sites. Bottom figure shows daily average for the same locations. Data reported in micro-Siemens per centimeter.

3.3.2.2 Temperature

When we plotted average temperature measurements for the Huelster monitoring well, the data plots substantially below the other three monitoring site results (Figure 31). The Huelster well's average water temperature was 22.37°C with a median value of 22.34°C. The highest daily average was 22.63°C on September 20, 2001, and the lowest daily average was 22.21°C on November 25, 2002. Breaks or small changes in temperature appear to correspond to pumping events.

The Hamilton windmill appears to be the most responsive to changes in conductivity and temperature, although not all changes in conductivity were accompanied with a change in water temperature. Daily variance indicates temperature spikes occurred on March 21, 2002; November 19, 2002; and January 14, 2003 (Figure 31). The average daily temperature was 25.05°C with a median value of 25.09°C. The highest daily average was 25.56°C on February 6, 2003 and the lowest daily average was 24.17°C on August 23, 2002.

San Solomon Springs showed the most scatter of daily variance in water temperature (Figure 31). The average daily temperature reading was 24.05°C with a median value of 24.01°C. Due to the amount of surface water in contact with the atmosphere, water temperatures appear to reflect seasonal and daily trends due to solar heating. The highest daily average water temperature was 24.91°C on May 14, 2002 and the lowest daily average was 22.52°C on February 7, 2003.

Phantom Lake Spring initial temperature and specific conductance recordings were deemed unreliable, although after the new transducer was installed on August 20, 2002 the transducer maintained a daily average temperature of 23.80°C, which appeared reasonable when compared to San Solomon Springs monitoring site.

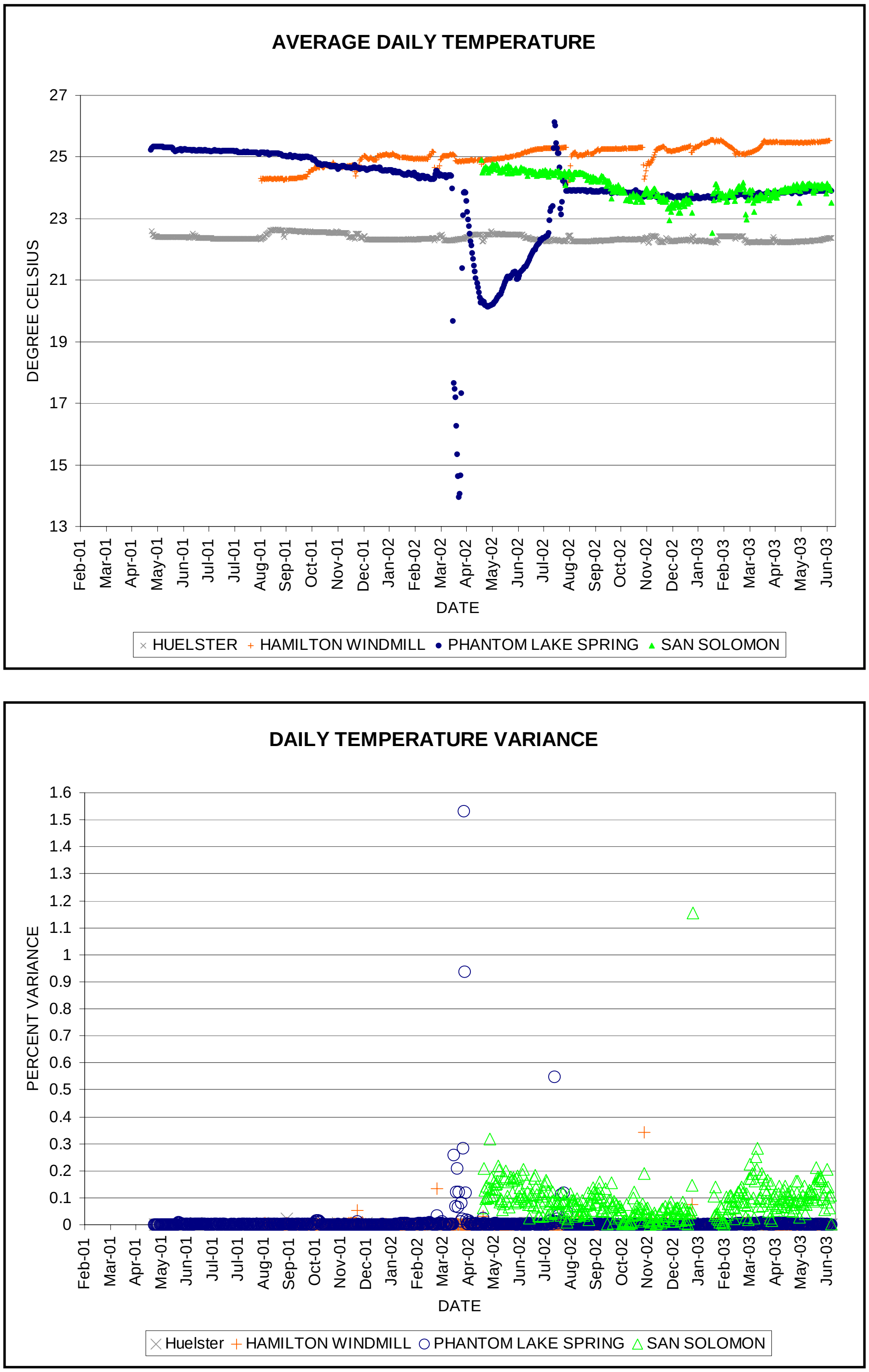


Figure 31. Top figure shows daily average temperature transducer measurements for Huelster, Hamilton Windmill, Phantom Lake, and San Solomon monitoring sites. Bottom figure shows daily variances for the same locations. Please note that the Huelster site is relatively constant and show little to no variance in the bottom figure.

3.3.3 Analytical Results

Groundwater samples can be classified into distinct chemical types based on the chemical and isotopic compositions. A chemical type of a groundwater may reveal where it is in a geochemical evolution sequence. Groundwater in recharge areas, discharge areas or in other locations along a flow path acquire characteristic compositions based on the type of chemical reactions between groundwater and aquifer materials, groundwater residence time, and mineralogy of the aquifer materials through which the water flowed. Initially, groundwater composition in the recharge areas may be dominated by calcium carbonate but the composition may progressively become enriched in sodium, chloride, or sulfate as water travels from the recharge to the discharge areas (Freeze and Cherry, 1979). The following sections discuss our analysis of the possible geochemical evolution of the waters in the study area.

3.3.3.1 Major Cation and Anion Analysis

We plotted the major cations and anions from the sampled wells (Figure 32) on a piper diagram to observe similarities or differences in water composition between samples obtained from the different hydrologic and geologic units. We observed that the chemical compositions of the waters plot into two general areas of the Piper diagram (Figure 33). Groundwater from the Davis Mountains shows a dominant calcium-sodium bicarbonate (Ca-Na-HCO_3) composition. Remainder of the groundwater samples from the Cretaceous and the Permian rocks, including the springs, show a dominant sodium - chloride sulfate (Na-Cl-SO_4) composition. Groundwater samples from Phantom Lake, San Solomon, and East Sandia springs have nearly identical compositions with the exception of a progressive increase in sulfate concentrations along its flow path. Sulfate increases from Phantom Lake Spring (463 milligrams per liter) to the San Solomon Springs (678 milligrams per liter) to the East Sandia Springs (992 milligrams per liter). Most of the sampled wells in Culberson County show a slightly higher level of sulfate (SO_4) than the spring waters.

We show the chemical compositions of the groundwater sampled during Phase I and Phase II investigations, supplemented with measurements from our groundwater database and previous studies, in Table 6. Sodium to chloride (Na/Cl) ratios of Phantom Lake, San Solomon, and East Sandia springs are nearly identical (0.63, 0.63, and 0.70, respectively). Sulfate to chloride (SO_4/Cl) ratios are also considerably lower in Phantom Lake, San Solomon, and East Sandia springs (0.69, 1.09, and 1.08, respectively) than the rest of the samples. All of the wells sampled (3, 4, and 8) from the northern slope of the Davis Mountains leading towards the springs and from Presidio County (sample 9) show much lower salinity [low sodium (Na), chloride (Cl), sulfate (SO_4), Strontium (Sr), and total dissolved solids (TDS)] compared to samples analyzed from the west and northwest of the study area.

Also important to note is that although samples 1 (Phantom Lake Spring) and 3 (Madera-Huelster well) are located in relatively close proximity to each other, their compositions are significantly different. This difference cannot be explained solely by differences in lithology. Groundwater samples from similar host-rock type show highly variable sodium to chloride ratios (Na/Cl), Strontium (Sr), and sulfate (SO_4) content (see samples 1 and 5 or 3 and 8 for comparison, Table 6). This variation in water chemistry may be due to discrete flow through fracture/fault systems that allow little or no mixing of these two nearby waters.

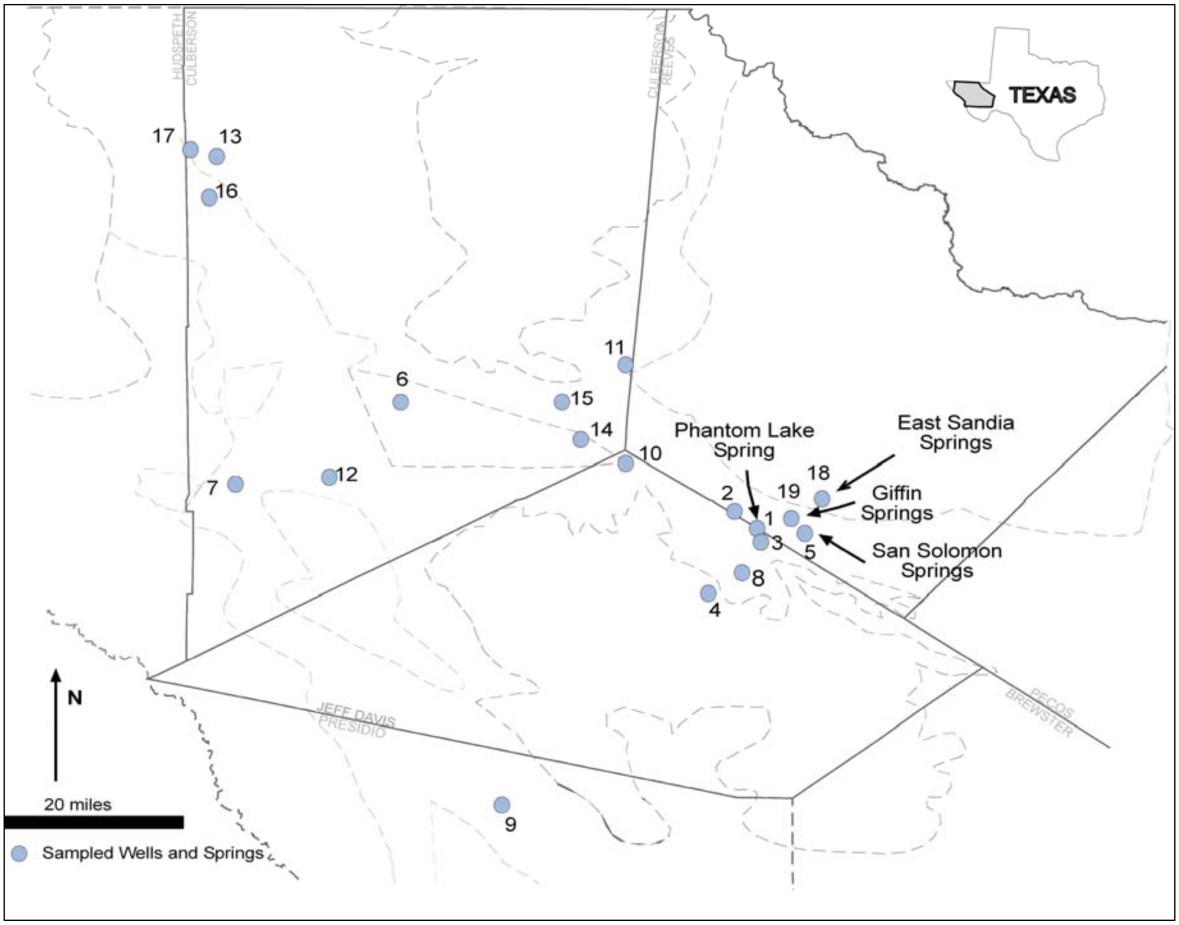


Figure 32. Map showing locations of the wells and springs that we sampled for isotopes and general chemistry. Corresponding state well numbers for each sample location are presented in Table 6. Dashed lines represent outline of major physiographic features in the study area (see Figure 1 for more details).

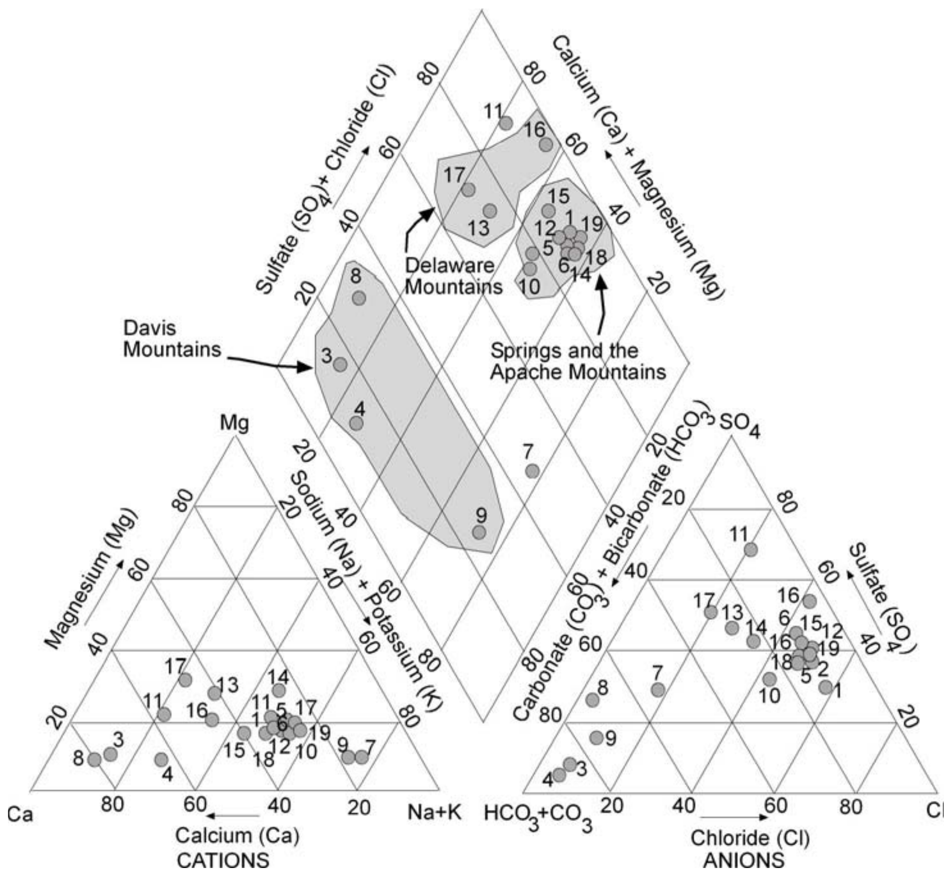


Figure 33. Piper plot diagram of the analyzed groundwater and spring water samples from the study area. Samples 3, 4, 8, and 9 (SWNs 5202404, 5209501, 5209303, and 5138803) are calcium-sodium bicarbonate (Ca-Na-HCO_3) type, and the remainder of the samples 1, 2, 5, 6, 7, 10, 11, 12, 13, 14, 15, 16, 17, 18 and 19 (SWN 5202405, 5201302, 5202611, 4752602, 4758505, 4764401, 748701, 4759603, 4718402, 4755802, 4755401, 4726101, 4717302, 5203115 and 5202610) are sodium-chloride sulfate (Na-Cl-SO_4) type. Note that all spring waters including Phantom Lake (1), San Solomon (5), East Sandia (18), and Giffin (19) springs cluster together in the Na-Cl-SO_4 fields.

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Table 6. Chemical composition of groundwater and spring water samples analyzed for this study. All values are in milligrams per liter (mg/l).

State Well Number (SWN)	Sample Number	Sample Names	Chemical Composition (mg/l)											
			Na	K	Ca	Mg	Cl	HCO_3	SO_4	NO_3	Sr	F	Na/Cl	SO_4/Cl
5202405	1	Phantom Lake Spring	418	22	175	79.9	664	224	463	1.04	3.43	2.24	0.63	0.70
5201302	2	Madera-McIntyre, Reeves	181	8.56	112	34.5	276	190	303	0.4	1.59	0.636	0.66	1.10
5202404	3	Madera-Huelster	11.7	2.75	58.3	5.05	8.6	173	12.8	5.93	0.254	0.5	1.36	1.49
5209501	4	Davis Boys Camp	14.3	2.18	31.9	3.02	4.54	114	4.97	2.33	0.10	1.4	3.15	1.09
5202611	5	San Solomon Spring	392	20.2	182	77.2	620	223	678	1.4	3.2	1.86	0.63	1.09
4752602	6	Apache Ranch	411	21.4	166	88.7	646	211	666	0.31	3.11	1.49	0.64	1.03
4758505	7	City of Van Horn	116	6.86	18.9	8.08	38.5	200	86.7	9.83	0.342	2.22	3.01	2.25
5209303	8	Timber Mountain	15	3.1	114	8.1	5.98	287	83	1.47	0.67	0.44	2.51	13.88
5138803	9	Clay Evans	85	4.2	18	6.5	15.2	212.3	36	2.37	0.29	2.31	5.59	2.37
4764401	10	Springhills Ranch	239	12.6	128	48.4	356	256	412	1.34	2.76	1.47	0.67	1.16
4748701	11	T-Diamond	173	9.48	422	96	217	213	1370	6.55	7.35	1.69	0.80	6.31
4759603	12	University Lands	375	18.4	124	76	541	263	557	0.51	2.98	1.4	0.69	1.03
4718402	13	Six Bar Cattle Co.	107	3.46	141	65	164	292	402	0.16	2.46	0.82	0.65	2.45
4755802	14	Yearwood Ranch	105	7.11	149	105	369	415	613	53.37	6.09	1.18	0.28	1.66
4755401	15	Yearwood Ranch	296		226	60	442	216	620	19		1.8	0.67	1.40
4726101	16	Wilson (Wimberly well)	371	90.3	497	135	600	90.31	1032		1.47	2.81	0.62	1.72
4717302	17	Armstrong Farms	83		156	66	117	298	411	0.4		1.4	0.71	3.51
5203115	18	East Sandia spring	444	23	202	88	630	281	680			2.1	0.70	1.08
5202610	19	Giffin Spring	463	25	186	79	628	276	679	1	4	2	0.74	1.08

We also analyzed water chemistry information from wells completed in specific geological units from four counties in and around the study area (Table 7). We observed that there is a high variability in the chemical composition within each of the geologic units. Chemical compositions from the Salt Bolson and the Delaware Mountain Group are similar to chemical compositions of the springs. Higher concentrations of Strontium (Sr) and Fluoride (F) are found in the waters from the Salt Bolson and the Delaware Mountain Group compared to waters from the Capitan reef complex and associated limestone, or waters from the Cretaceous system.

Table 7. Groundwater compositions from wells completed in the Capitan Reef and associated limestones, Cretaceous System, Salt Bolson, and the Delaware Mountain Group from Jeff Davis, Culberson, Reeves, and Presidio counties. Mean and standard deviation values are shown in parentheses. N represents number of total samples used in estimating the mean and the standard deviation.

Formation	Sodium/ Chloride (Na/Cl)	Sulfate/ Chloride (SO_4/Cl)	Strontium (mg/l)	Fluoride (mg/l)
Capitan Reef Complex and associated limestone	0.04 to 6.45 (1.28±1.38, n = 40)	0.37 to 368 (10.47 ± 40.30, n = 50)	0.34 to 5.52 (2.41± 1.60, n = 17)	0.55 to 3 (1.38± 0.71, n = 40)
Cretaceous System	0.6 to 1.64 (1.14±0.34, n = 9)	0.52 to 5.79 (3.24 ± 2.07, n = 10)	0.7 to 5.75 (4.06 ± 2.9, n = 3)	0.6 to 2.5 (1.38 ±0.78, n = 9)
Salt Bolson and Delaware Mountain Group	0.54 to 0.71 (0.63±0.07, n = 5)	1.67 to 4.51 (2.81± 1.09, n = 5)	6.7 to 14.4 (10.5 ± 5.42, n = 3).	1.5 to 1.89 (1.86 ± 0.35, n = 3)

Chemical composition of groundwater is largely determined by chemical reactions between the flowing water and host-rock mineralogy. Chemical reactions may occur in the form of dissolution, precipitation, ion exchanges, and denitrification processes. These reactions can be evaluated by making cross-plots of the individual ions according to their stoichiometric compositions. When these ions plot on a straight line, a specific reaction is inferred and a deviation from it indicates involvement of other processes that changes the composition (Figures 34, 35, 36 and 37).

When we plotted the sodium (Na) and the chloride (Cl) values of the waters, we observed that most of the samples fall on the 1:1 line (Figure 34). Samples 7 and 9 have slightly higher sodium (Na) values and sample 14 has lower sodium (Na) values compared to chloride (Cl). The close correlation for most of the samples indicates that most of the sodium (Na) and chloride (Cl) were derived from dissolution of halite minerals. The characteristic sodium to chloride (Na/Cl) weight ratios (0.62 to 0.63) of the samples agree with groundwater derived from halite dissolution. Calcium to sodium (Ca-Na) exchange proved to be insignificant except for samples 3, 4, 7, 8, 9, and 14.

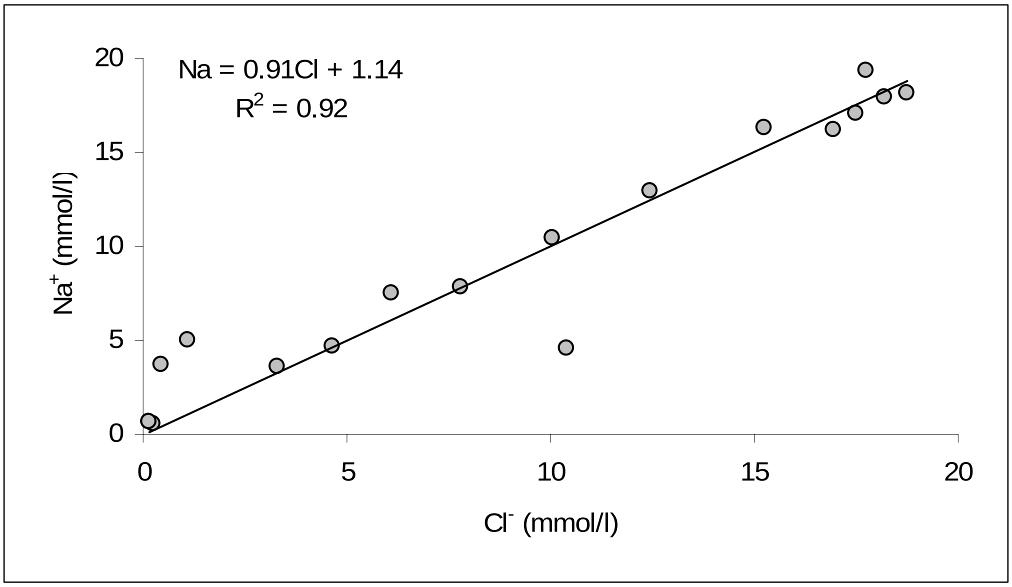


Figure 34. Plot of sodium (Na^+) versus chloride (Cl^-) of water samples in the study area.

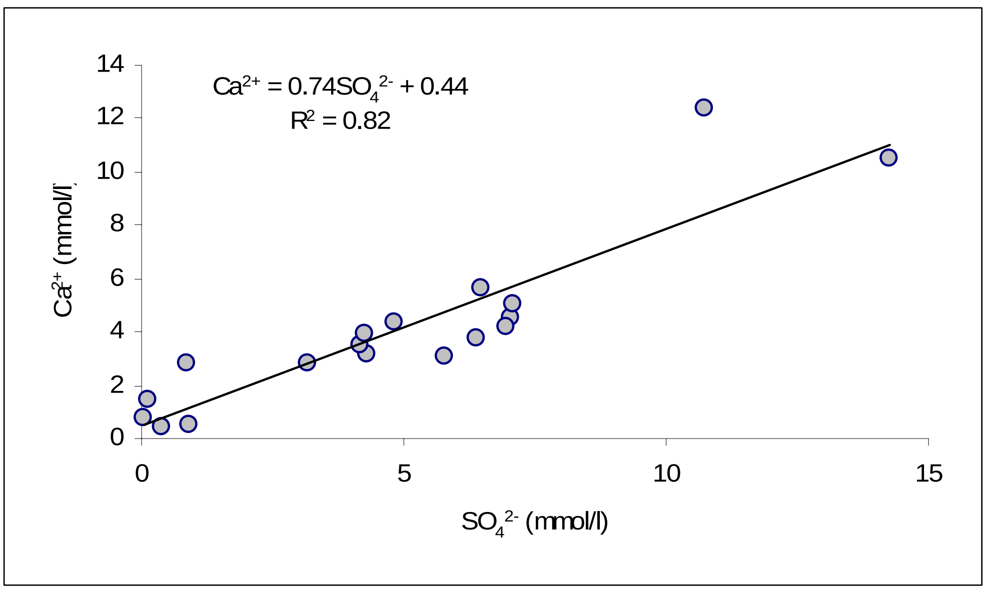


Figure 35. Plot of calcium (Ca^{2+}) and sulfate (SO_4^{2-}) of the sampled water. Solid line represents linear regression of the data.

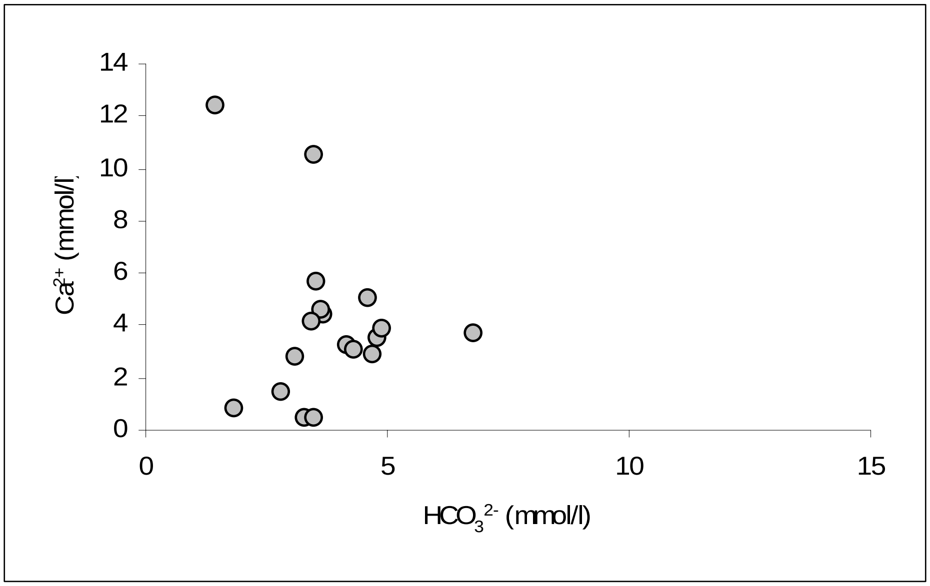


Figure 36. Plot of calcium (Ca^{2+}) and bicarbonate (HCO_3^{2-}) of the sampled water.

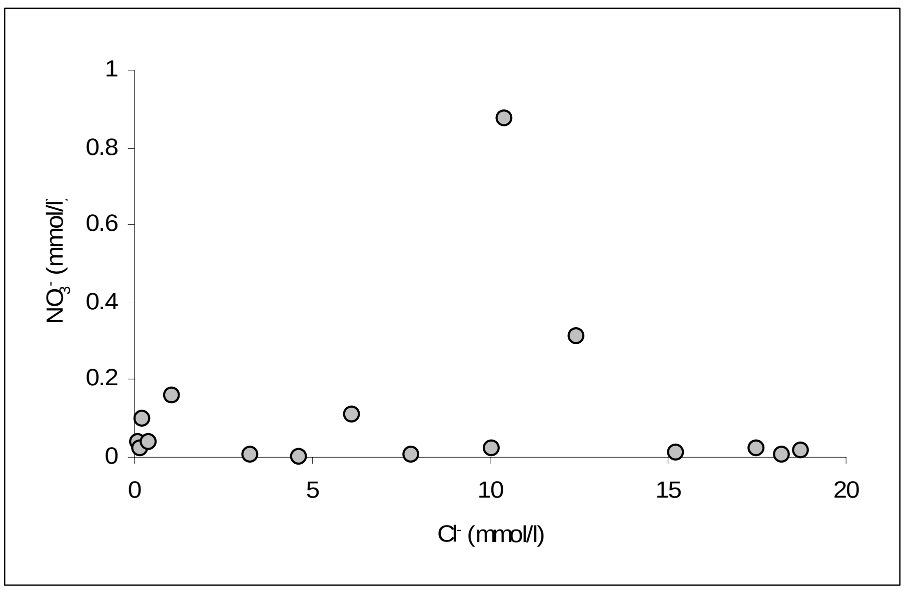


Figure 37. Plot of nitrate (NO_3^-) versus chloride (C^{l-}) of the sampled water.

The sodium to chloride (Na/Cl) ratios we observed in the springs are close to what would be expected from dissolution of pure halite (0.65), which is maintained in solution unless significant cation exchange that reduces sodium (Na^+) concentration occurs (Hitchon and others, 1969; Leonard and Ward, 1962; and Richter and Kreitler, 1991). Similar sodium to chloride (Na/Cl) ratios (0.63 to 0.65) in the salt springs of West Oklahoma were reported to have been derived from halite solution (Leonard and Ward, 1962). Other researchers reported that high sodium to chloride (Na/Cl) ratios could even be observed in shallow alluvium due to halite dissolution in the underlying aquifers (Gogel, 1981).

A plot of calcium (Ca^{2+}) and sulfate (SO_4^{2-}) of the waters show a reasonable correlation ($r^2 = 0.81$) perhaps indicating that dissolution of gypsum must also have been a significant source for much of the calcium in the waters (Figure 35). A plot of calcium (Ca^{2+}) and bicarbonate (HCO_3^-) of the waters indicate a poor correlation ($r^2 = 0.04$) (Figure 36) suggesting that most of the calcium in the studied waters may not have been entirely derived from dissolution of carbonate sediments. A plot of chloride (Cl^-) and nitrate (NO_3^-) of the waters show a wide scatter (Figure 37) suggesting that the sources of nitrate and chloride are not the same. In other words, chloride (Cl^-) ions could not have been derived from irrigation return water except for samples 14 and 15, both of which are located in the same general area and show high levels of nitrate (Table 6).

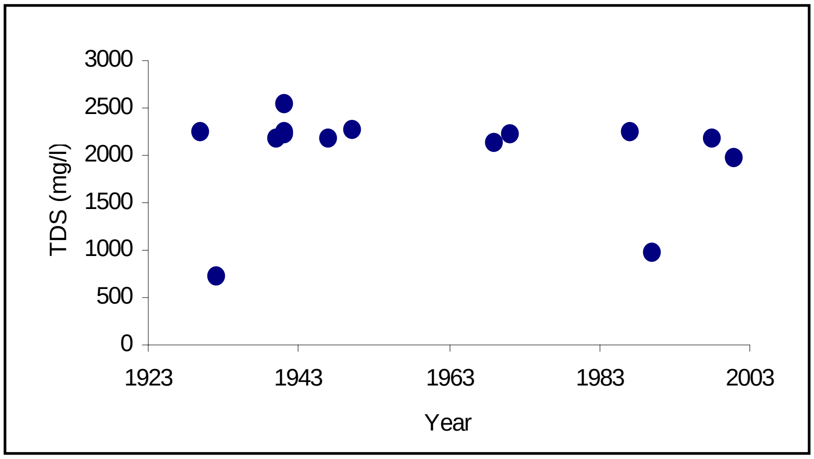
We also plotted the total dissolved solids (TDS) and sodium to chloride (Na/Cl) concentrations of Phantom Lake and San Solomon spring waters over the historical record (1923 to 2003) to observe any changes in water quality (Figure 38). We observed that the total dissolved solids concentrations in both the springs remain steady except during 1932 and 1990 when marked decreases occur in the total dissolved solids values. A marked increase in spring flow and rainfall occurs at the same time (LaFave and Sharp, 1987). A plot of the sodium to chloride (Na/Cl) ratios show a wide spread of values (0.6 to 0.83) with the highest excess sodium (Na^+) found in the 1932 water sample. Although there is dilution of the spring waters through additional flow, excess sodium (Na^+) is not observed in the 1990 samples (Figure 39).

3.3.3.2 Isotope Analysis

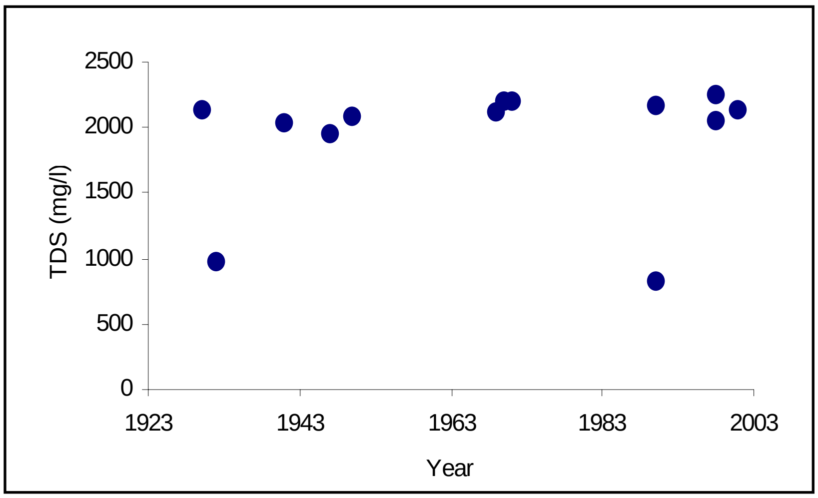
We analyzed eighteen samples of groundwater, spring water, and rainwater for chemical and isotopic compositions. These samples were taken from locations along the northern slope of the Davis Mountains leading towards the springs and from various locations in and around the Apache and the Delaware Mountains to the west and northwest of the study area (Figure 32). We sampled groundwater at locations near the shallow outcrop and near discharge areas irrespective of the lithology to determine geochemical evolution of the waters.

3.3.3.2.1 Oxygen-18 ($\delta^{18}O$) and Deuterium (δ^2H)

Isotopes of Oxygen-18 ($\delta^{18}O$) and Deuterium (δ^2H) partition into different fresh water reservoirs as water evaporates from the oceans, rainout, snow, ice accumulation and melting, and runoff (Clark and Fritz, 1997). Although large partitioning of Oxygen-18 ($\delta^{18}O$) and Deuterium (δ^2H) isotopes may occur during these processes, most of the fresh waters surprisingly correlate well on a global scale (Craig, 1961). Most of the fresh waters fall along a global meteoric water line (GMWL) on an Oxygen-18 ($\delta^{18}O$) and Deuterium (δ^2H) plot (Craig, 1961). GMWL is essentially an average of the numerous local and regional meteoric water lines defined by the following equation:

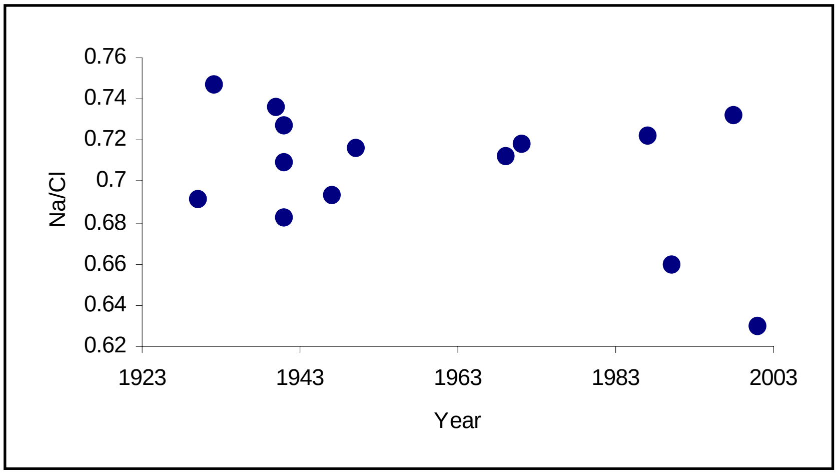


Phantom Lake Spring changes in total dissolved solids (TDS)

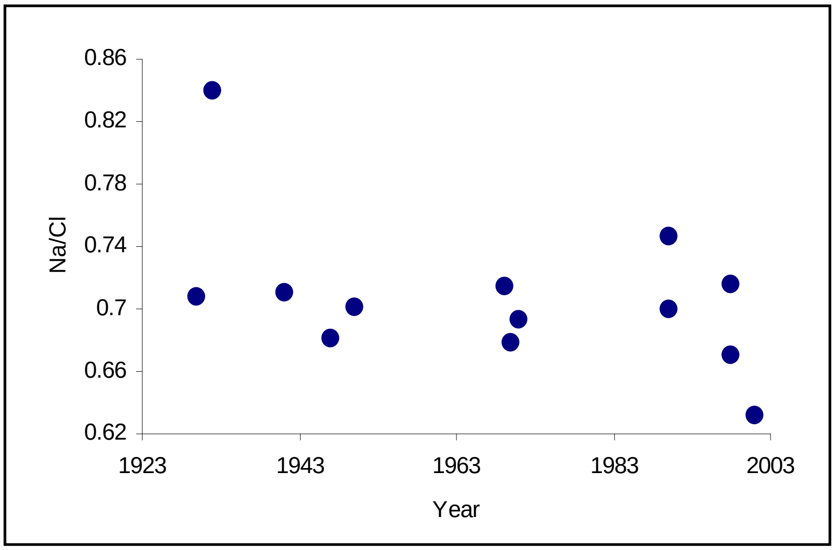


San Solomon Springs changes in total dissolved solids (TDS)

Figure 38. Comparison of changes in total dissolved solids (TDS) in Phantom Lake Spring versus San Solomon Springs over time.



Phantom Lake Spring changes in sodium to chloride ratios



San Solomon Springs changes in sodium to chloride ratios

Figure 39. Comparison of changes in sodium to chloride ratios in Phantom Lake Spring and San Solomon Springs.

[Equation 1] $\delta^2H = 8\delta^{18}O + 10\ ^{o}/_{oo}$ SMOW (Standard Mean Ocean Water: Craig, 1961).

Craig (1961) observed that isotopically depleted waters are associated with cold regions and isotopically enriched waters occur in warm regions. Therefore, isotopic evolution of the waters can be determined based on how Oxygen-18 ($\delta^{18}O$) and Deuterium (δ^2H) isotope values are positioned with respect to the GMWL.

Climate change is brought about by changes in temperature and precipitation. Temperate climates have undergone rapid changes in temperature and precipitation since late Pleistocene times (Clark and Fritz, 1997). Isotopic compositions of seawater in Archean and Proterozoic times were depleted by about eight parts per thousand ($^{o}/_{oo}$) in Oxygen-18 ($\delta^{18}O$) suggesting that the early earth's oceans were warmer than today (Clark and Fritz, 1997). Isotopes are a useful tool for interpretation of climatic conditions under which fossil or paleogroundwater recharged. A shift in the isotopic signatures, isotope values plotting along the GMWL or below it, may indicate existence of a pluvial (humid) climate during recharge of the paleogroundwater. Water also becomes progressively enriched in Oxygen-18 and Deuterium isotopes by evaporation before rainfall hits the ground, from the unsaturated zone, or in a closed basin where the water table is exposed to the atmosphere (Gonfiantini, 1986).

The analyzed groundwater and spring water samples have Oxygen-18 values that range from –6.8 to –9.3 parts per thousand SMOW and Deuterium values that range from -52 to -72 parts per thousand SMOW. One rain sample analyzed that we collected during the study was considerably enriched in both Oxygen-18 and Deuterium isotopes (Figure 40, Table 8). We observed that most of the Oxygen-18 and Deuterium isotopes plot parallel to but positioned lower than the GMWL. Occurrence of the isotope compositions parallel to but just below the GMWL line may suggest that much of the recharge may have occurred under direct infiltration through faults or buried alluvial channels within a sediment sequence under a humid climate. When we use linear regression of the isotope values of the waters excluding the rainwater, we obtain an equation defined by:

[Equation 2] $\delta^2H = 6.22\delta^{18}O - 7.45$

indicating a shift in the slope compared to the GMWL, which is probably due to evaporation. Allison and others (1984) postulated that when recharge occurs under direct infiltration and a steady-state condition is reached, groundwater isotopic composition approaches a mixture of the pre-existing soil moisture and rainfall composition.

Groundwater samples from wells 3, 4, 8, and 9 from the Davis Mountains have considerable similarities in both Oxygen-18 (–7.4 to –7.6 parts per thousand SMOW) and Deuterium values (–52 to –57 parts per thousand SMOW) (Figures 40, 41, 42, and 43 and Table 8). Similar Oxygen-18 (-6.8 to –7.7 parts per thousand SMOW) and Deuterium (-52 to -54 parts per thousand SMOW) values are found in wells 11, 14, and 15 located along the county lines of Jeff Davis, Culberson, and Reeves counties. Wells from the Davis Mountains (3, 4, 8, and 9) occur at higher elevations than the wells (11, 14, and 15) located along Jeff Davis, Culberson, and Reeves county lines. There is nearly a thousand foot elevation difference between the two general locations. These waters are enriched in both Oxygen-18 and Deuterium isotope values. The rest of the samples (1, 2, 5, 6, 7, 12, 13, 16, and 17) have considerably more depleted Oxygen-18 (–8.5 to –9.3 parts per thousand SMOW) and Deuterium (–60 to –72 parts per thousand) values (Table 8).

Rainfall occurs as an air mass rises over a landscape and cools by expansion. The cooler temperatures at higher altitudes cause depletion in both the Oxygen-18 and Deuterium isotope values. Clark and Fritz (1987) report that Deuterium isotope depletion varies from –1 to -4 parts per thousand with a lower variation of –0.15 to –0.5 parts per thousand in Oxygen-18 isotopes for every 300 feet rise in altitude. Therefore, recharge from direct rainfall in the Davis Mountains wells (at approximately 4,400 feet elevation) would likely be more depleted than wells located in the area of Jeff Davis, Culberson, and Reeves county lines (at approximately 3,400 feet elevation). However, we do not observe any significant differences in the isotope values between these two areas. Therefore, if the water in this area receives flow from the Davis Mountains, the original isotopic composition were altered by mixing of water sourced from local recharge and/or mixing of water derived from a regional source.

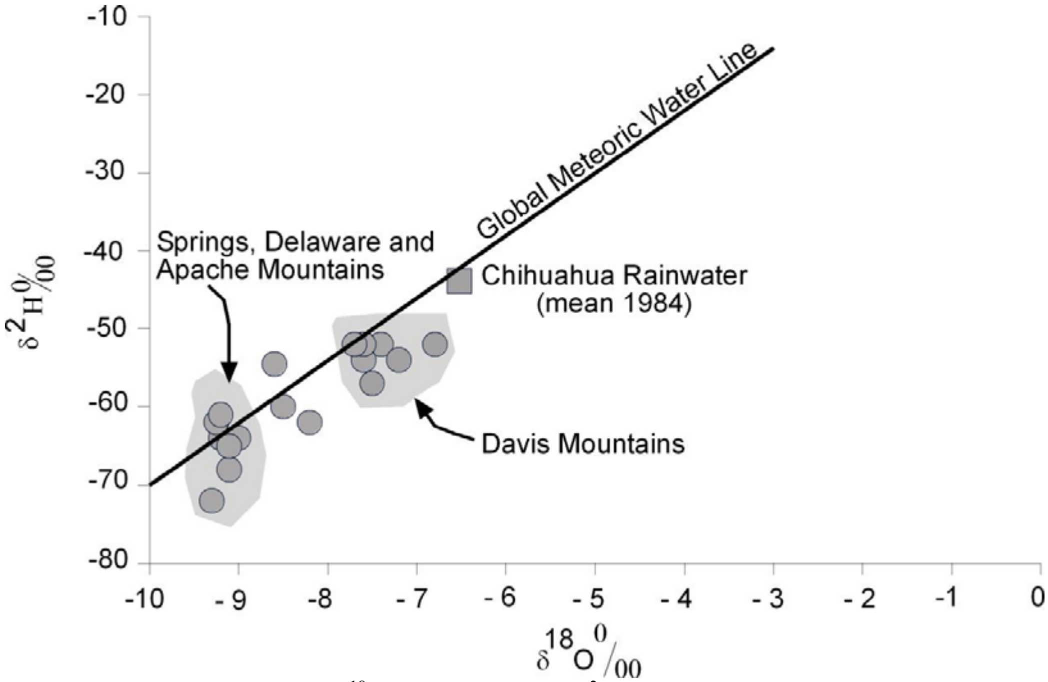


Figure 40. Plot of Oxygen-18 ($\delta^{18}O$) and Deuterium (δ^2H) isotope values of the analyzed waters. Global meteoric water line indicated by a solid line (Craig, 1961). Mean of rainfall values for 1984 from Chihuahua, Mexico was plotted for comparison.

Table 8. Isotope values of the analyzed water samples from the study area. SMOW refers to standard mean ocean water, TU to Tritium unit, BP to before present, fmdn to fraction modern, PDB to Pee Dee Belemnite standard, CDT to Cannon Diablo Troilite, and NM not measured.

Sample Number	Well Number	^{18}O‰ (SMOW)	δ^2H ‰ (SMOW)	Tritium	Apparent ages (BP)	^{14}C fmdn	^{14}CpmC	$^{13}C/^{12}C$‰ PDB	^{34}S‰ CDT
1	5202405	-9.2	-64	0.06	17,580	0.112	11.2	-7.4	10.6
2	5201302	-8.5	-60	0.12	11,290	0.245	24.5	-7.3	NM
3	5202404	-7.4	-52	1.87	2,670	0.717	71.7	-11.8	NM
4	5209501	-7.5	-57	0.24	8,830	0.333	33.3	-12.7	NM
5	5202611	-9.1	-68	0.17	15,360	0.148	14.8	-7.3	10.3
6	4752602	-9.3	-72	-0.06	19,200	0.092	9.2	-6.8	11.3
7	4758505	-8.2	-62	0.01	17,950	0.107	10.7	-6.6	8.2
8	5209303	-7.6	-54	1.36	11,410	0.242	24.2	-8.7	NM
9	5138803	-7.6	-52	0	14,630	0.162	16.2	-8.2	NM
10	4764401	-8.6	-54.5	2.12	10,220	0.2801	28.01	-7.4	NM
11	4748701	-7.7	-52	0.61	4,250	0.5889	58.89	-7.8	NM
12	4759603	-9.25	-62	0.12	17,140	0.1183	11.83	-6.2	NM
13	4718402	-9.2	-61	0.02	16,970	0.1209	12.09	-8.7	NM
14	4755802	-7.2	-54	NM	17,690	0.1105	11.05	-9	3.2
15	4755401	-6.8	-52	4.26	NM	NM	NM	NM	10
16	4726101	-9	-64	0.08	NM	NM	NM	NM	11.1
17	4717302	-9.1	-65	NM	16,090	0.1349	13.49	-8.6	11
	Rain water	-1.2	-15.5	NM	NM	NM	NM	NM	NM

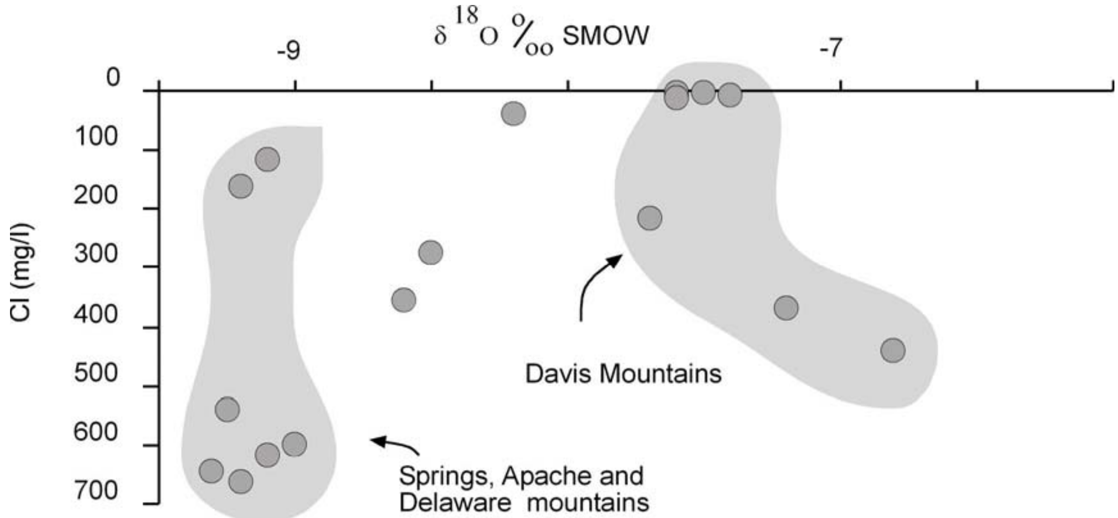


Figure 41. A cross-plot of chloride and Oxygen-18 isotopes of the analyzed waters. Samples with higher chloride concentrations have lighter Oxygen-18 values.

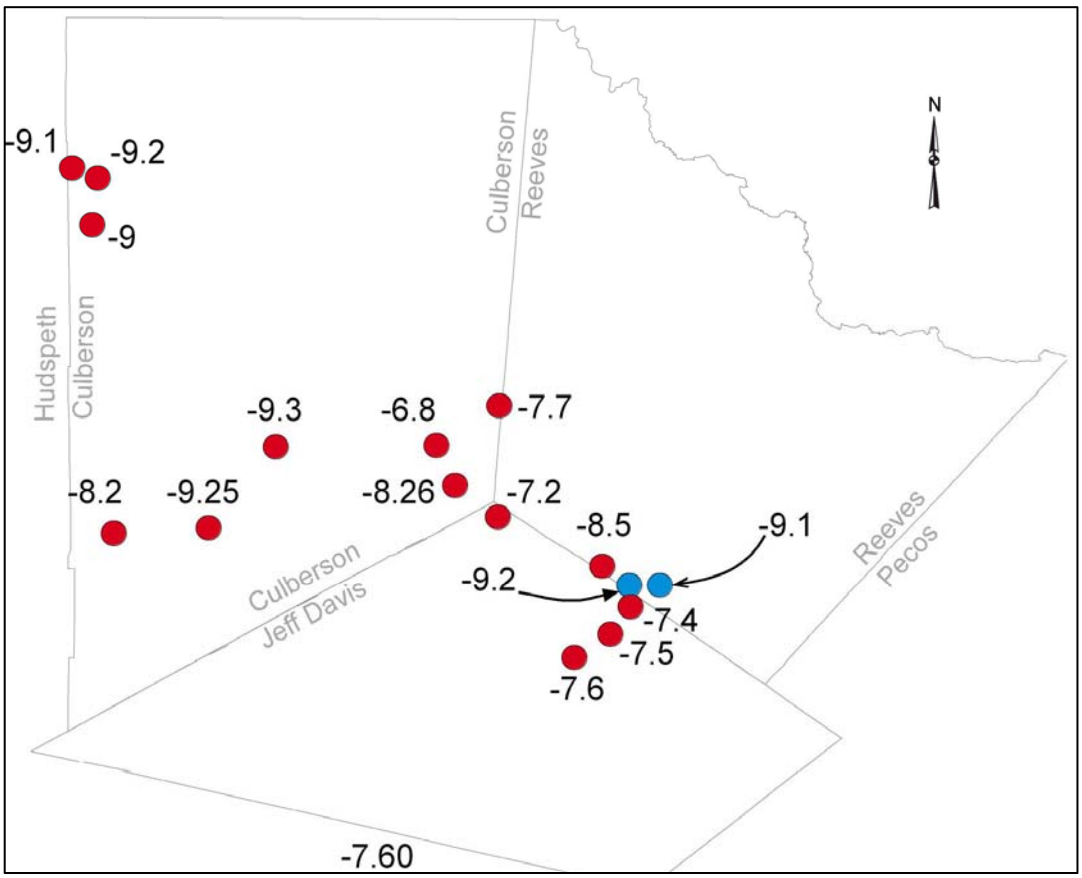


Figure 42. Distribution of oxygen isotopes in the groundwater and the spring waters of the study area.

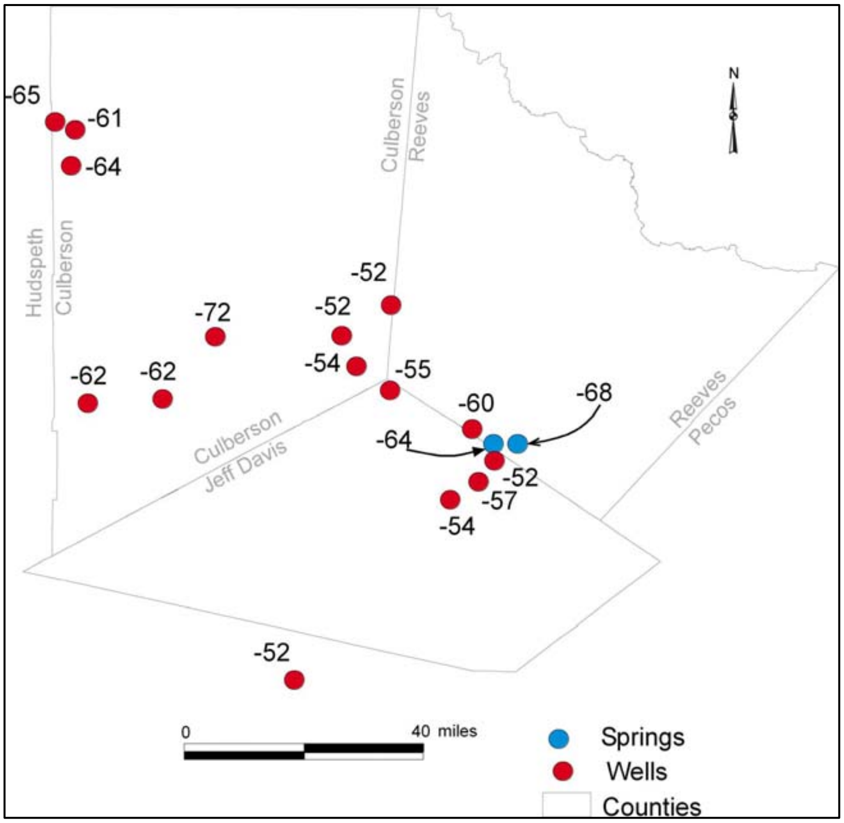


Figure 43. Distribution of Deuterium isotopes in the groundwater and the spring waters of the study area.

Any seasonal fluctuations that may occur in rainfall seldom are exhibited in groundwater samples as most of these variations are attenuated prior to reaching the confined portions of an aquifer. This attenuation of seasonal variation in the isotope values depends on a number of factors including physical characteristics of the unsaturated zone, length of the flow path, and residence time (Younge and others, 1985). Isotopic measurements of Oxygen-18 during March and June 1995 from Phantom Lake, San Solomon, and Giffin springs indicate no changes in values (LaFave and Sharp, 1987). Similarities in composition may suggest that these waters are perhaps largely unaffected by changes in local climate which would be the case if they were derived from older fossil waters.

Isotopes of Oxygen-18 and Deuterium of the only rainwater sampled is much heavier than the groundwater samples. We collected this rainwater sample in August at the start of the rainy season when most of the heavy isotopes could potentially have been trapped in the initial vapor mass. Thus, this isotope value perhaps represents a heavier end-member that could be encountered in a wider spread of isotopic compositions in any rainfall. For example, Oxygen-18 and Deuterium values of rainfall (1962 to 1988) from the closest global network for isotopes in precipitation (GNIP) station in the Chihuahua Desert in northwestern Mexico indicate that the isotope values in the rainfall can vary widely. In the Chihuahua Desert, Oxygen-18 values of the rainfall range from zero to –14.3 parts per thousand (-6.52 ±3.40 parts per thousand SMOW) and Deuterium values range from –9.9 to –96.9 parts per thousand (-43.9 ± 25.25 parts per thousand SMOW).

Several researchers have suggested that the ground temperatures may have fluctuated from five to eight degrees Celsius between the last glacial maximum and the present (Dutton, 1995; Stute and others, 1995). Dansgaard (1964) reported a relationship between surface air temperature and Oxygen-18 values with a slope of 0.695 parts per thousand per degree Celsius. Uliana (2000) reported that this temperature reduction may translate to a depletion in Oxygen-18 isotope values of the rainfall during the last glacial maximum by about three to five parts per thousand SMOW for our study area. If we add this conversion to our lone rainfall value, the Oxygen-18 value of the rainfall in the last glacial maximum could have been –6.2 parts per thousand SMOW closer to the mean value of the present day rainfall in the Chihuahua Desert. If we apply this conversion to the Chihuahuan samples, we observe that Oxygen-18 isotope values in the rainfall during the last glacial maximum could range from –5 to –19.3 parts per thousand. These values are within the range of values observed in the groundwater and spring water samples from our study area.

A plot of chloride versus Oxygen-18 values indicates that the waters with higher chloride concentrations, an indicator of increased water-rock interaction and therefore increased residence time, show lighter values (Figure 41). Five samples (1, 5, 6, 12, and 16) that could presumably lie along a northwest to southeast flow path cluster together in the plot. Although samples 13, 16, and 17 are located in close proximity, they show considerable differences in chloride but not in Oxygen-18 values. Samples 13 and 17 have higher sodium to chloride ratios than sample 16 indicating gain of sodium through cation exchange. Most of the samples from the Davis Mountains have the least chloride salinity and plot along the x-axis.

3.3.3.2.2 TRITIUM

Tritium (δ^3H) isotopes that are naturally produced from cosmic radiation are low and maintain a secular equilibrium between production and decay. The bulk of Tritium is derived from atmospheric testing of thermonuclear bombs between 1951 and 1980. Most of the “bomb” Tritium has been lost through natural decay leaving Tritium levels in global precipitation closer to natural levels (Clark and Fritz, 1997). Only qualitative interpretations can be made from Tritium isotopes due to mixing with pre-bomb groundwater and natural decay of Tritium. A qualitative groundwater age can be determined based on Tritium concentrations:

(1) Tritium at less than 0.8 TU indicates recharge prior to 1952,
(2) 0.8 to 4 TU indicates a mixture between submodern and recent recharge,
(3) 5 to 15 TU indicates modern waters (less than 5 to 10 years), and
(4) greater than 50 TU places groundwater from mainly 1960s recharge when it peaked (Clark and Fritz, 1997).

Isotopes of Tritium in the groundwater from wells (3, 4, 8, and 9) in the Davis Mountains show an increase in values down slope towards the springs (Table 8, Figure 44). Tritium values for the sampled waters along the Davis Mountains are 0.24, 1.36, and 1.87 indicating that the waters represent pre-1952 recharge to a mixture of sub-modern and recent recharge. Increasing Tritium values in the waters down slope of the Davis Mountains probably suggest mixing with younger recharge. Further west, sample 10 and sample 15 contain much lighter values (2.12 TU and 4.26 TU, respectively). The spring waters (Phantom Lake and the San Solomon) and the rest of the groundwater samples west of the Apache Mountains indicate low Tritium values (0.06 and 0.17, Table 8) indicating that they are produced from pre-1952 recharge events. Thus, the considerable differences in Tritium values similarly identify two sources of water – one in the south from the Davis Mountains and the other west to northwest of the Apache Mountains and beyond.

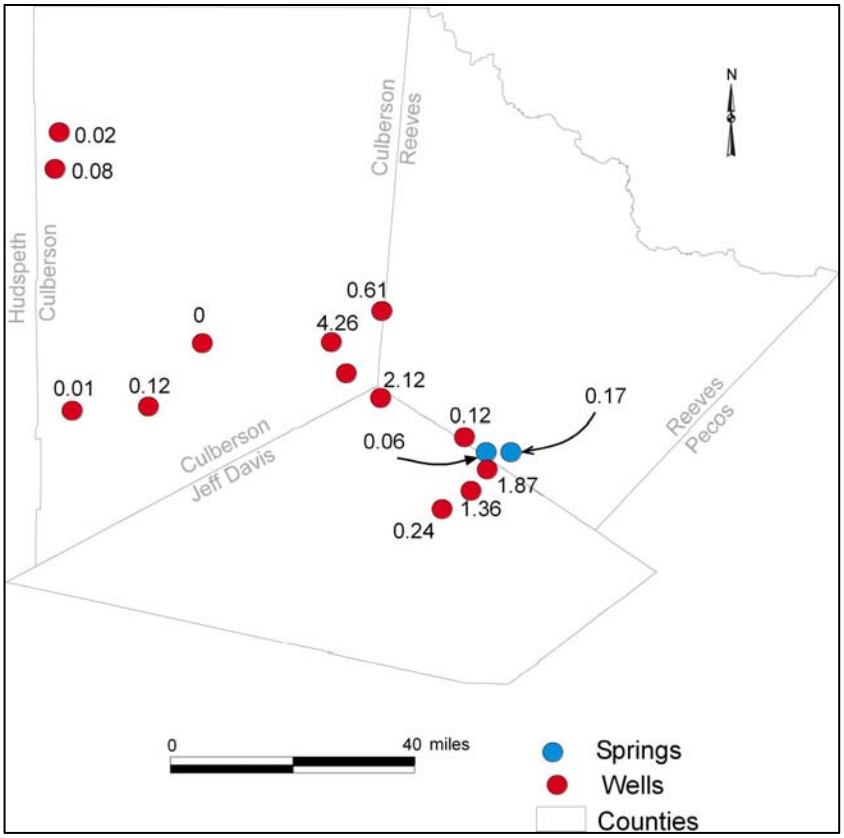


Figure 44. Distribution of Tritium isotopes in the groundwater and the spring waters of the study area.

The Tritium isotope value of the lone rain sample from Pecos County is 2.92 TU (location not shown in Figure 44). This value is somewhat lower than what would be expected in a modern rainfall particularly when one groundwater sample has considerably more Tritium than the rain sample. This depletion may indicate that much of the bomb Tritium is slowly being lost through natural decay from the atmosphere. Monthly Tritium values in the rainfall from the Chihuahuan Desert global network for isotopes in precipitation (GNIP) station in 1984 recorded from seven to 17.5 TU.

3.3.3.2.3 CARBON ISOTOPES

Tritium-free groundwater can be considered sub-modern (recharged at greater than 50 years) or older and to not incorporate any significant component of modern water. Paleogroundwater can be dated for its age by Carbon-14 (^{14}C) isotopes. Carbon-14 is derived from the decay of photo-synthetically fixed-carbon in the soil that reaches the groundwater either in the form of dissolved inorganic carbon (DIC) or dissolved organic carbon (DOC). The age dating method involves determination of the loss of radionuclide (^{14}C) in the sample assuming that the initial concentration of the parent is known and that no gains or loss occurred except through decay. The half-life of Carbon-14 is about 5,730 years and the effective dating range for groundwater is about 30,000 years (Clark and Fritz, 1998). The usual expression of Carbon-14 activity is as a percent of the initial Carbon-14 activity, in other words, percent modern Carbon (pmC). A larger Carbon-14 activity of a sample compared to percent modern Carbon suggests that the sample is younger in age.

Carbon-14 activity of the groundwater samples range from 9.2 to 71.7 percent modern Carbon (Table 7). Samples 3, 4, 8, 10, and 11 have higher Carbon-14 percent modern Carbon values (71.7, 33.33, 24.2, 28, and 58.89 percent modern Carbon, respectively) than the rest of the samples (9.2 to 24.5 percent modern Carbon). We observed an anomalous increase in Carbon-14 values in the Davis Mountains samples – samples upslope have much lower values than down slope . Assuming that recharge in the Davis Mountains taking place at higher elevations, higher Carbon-14 activity would be expected at higher elevations and lower activity in the discharge areas at lower elevations. However, the anomalous trend in Carbon-14 activity down slope could only be explained by mixing with younger water or due to carbonate mineral reactions resulting in resetting of Carbon-14 activity.

Although Tritium and Carbon-14 are used as age dating tools for modern and older fossil groundwater, we plotted these two parameters to see if they had a relationship (Figure 45). We observed that there is a progressive increase in Carbon-14 percent modern Carbon with an increase in Tritium (TU) with the exception of samples 8 and 10 that probably do not follow the trend due to carbonate reactions. Therefore, Tritium and Carbon-14 percent modern Carbon apparent ages of the waters are consistent for most of the samples. Furthermore, similarities in Tritium and Carbon-14 percent modern Carbon apparent ages may suggest that Carbon-14 percent modern Carbon values were probably more altered by natural decay rather than carbonate mineral reactions and mixing with younger water.

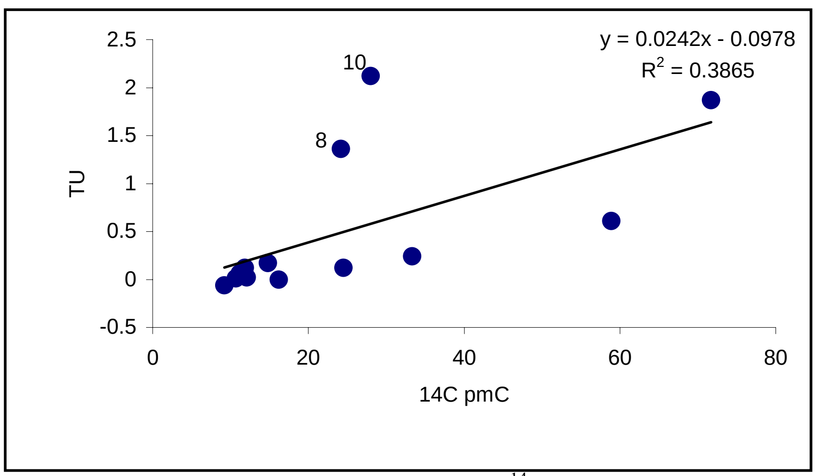


Figure 45. A cross-plot of Carbon-14 percent modern Carbon (^{14}C pmC) versus Tritium (TU) for the analyzed water samples. Solid line represents the linear regression of data.

Carbon-13 to Carbon-12 ($^{13}C/^{12}C$) ratios are a good indicator for determining open versus closed system evolution of carbonate in groundwater. This is because there is a large difference between Carbon-13 to Carbon-12 values in the soils and the carbonate matrix of the aquifer. Under an open system condition of an unconfined aquifer, Carbon-13 to Carbon-12 ratios in the groundwater approach the soil values (-15 parts per thousand Pee Dee Belemnite standard). However, under a closed system condition of a confined aquifer, Carbon-13 to Carbon-12 ratios values commonly become heavier reflecting reactions with the aquifer matrix (greater than or equal to -15 parts per thousand Pee Dee Belemnite standard). Samples 3 and 4 have the most depleted Carbon-13 to Carbon-12 values (Table 8). A cross-plot of the Carbon-13 to Carbon-12 ratios and the Carbon-14 values indicate that the Carbon-13 to Carbon-12 ratios progressively decrease with an increase in the Carbon-14 percent modern Carbon values (Figure 46). We can therefore suggest that the depleted values (samples 3 and 4) reflect groundwater derived under shallow, unconfined conditions that retained the Carbon-13 to Carbon-12 ratio signatures of the soils. The heavier isotopes suggest that the groundwater flowed under confined conditions where a longer residence time allowed reactions with the carbonate matrix of the aquifer materials.

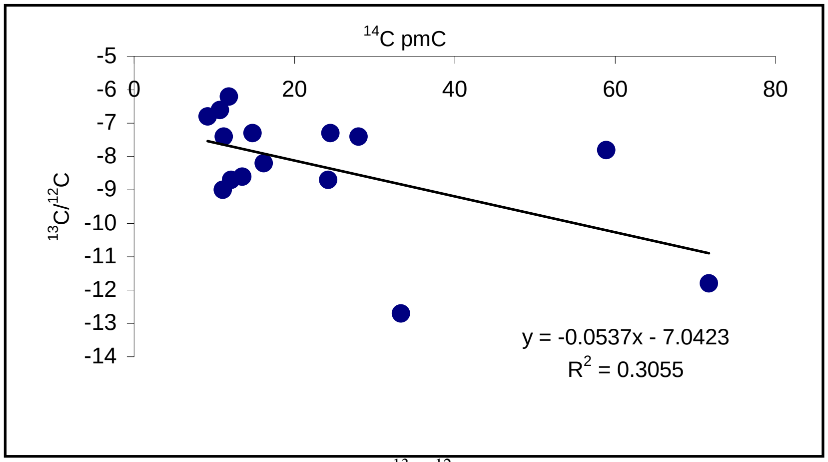


Figure 46. A cross-plot of Carbon-13 to Carbon-12($^{13}C/^{12}C$) ratios versus Carbon-14 percent modern Carbon (^{14}C pmC) shows that samples with higher Carbon-14 percent modern Carbon have lighter Carbon-13 to Carbon-12 values. Solid line represents the linear regression of data.

To determine the correct Carbon-14 ages, we considered different age correction models to revise the apparent radiocarbon ages (see NETPATH simulation results). Apparent radiocarbon ages do not account for any of the chemical reactions that change the Carbon-14 values but only the natural decay. The correction method incorporates various models such as alkalinity, statistics, Carbon-13 (^{13}C) mixing, and matrix-exchange to resolve carbonate reactions effects on Carbon-14 values. We present a summary of the age corrections below. Chowdhury and others (2004a, b) provides are correction details.

The alkalinity model uses a correction that incorporates the initial and the final dissolved inorganic carbon concentration, which normally amounts to about 50 percent in the vast majority of samples for closed system dissolution of calcite (Tamer, 1975). This is because most of the carbonic acid (H_2CO_3) is consumed by limestone dissolution when the original Carbon-14 activity of the soil carbon dioxide (CO_2) gas is diluted by about 50 percent. We used this value for estimating alkalinity correction.

The statistical correction approach assumes that during infiltration of the water some the Carbon-14 free carbon may dilute the Carbon-14 activity. This value can be estimated statistically over the recharge area, which could act as the Carbon-14 activity of the aqueous carbonate. Vogel (1970) presents the dilution values for different geologic systems: karst equals 0.65 to 0.75, fine-grained carbonates equals 0.75 to 0.90, and crystalline rocks equals 0.90 to 1.00.

The Carbon-13 (^{13}C) mixing model allows for incorporation of Carbon-14 active dissolved inorganic carbon during open system dissolution and their dilution under closed system condition as it so commonly occurs in nature (Pearson and Hanshaw, 1970). However, the dilution factor is heavily weighed on pH-dependent enrichment between soil carbon dioxide (CO_2) and aqueous carbon in the recharge areas.

The matrix exchange approach looks into Carbon-14 enrichment between carbonate minerals of the aquifer matrix and the dissolved inorganic carbon (Fontes and Garnier, 1979). In this method, the Carbon-14 activity is apportioned between (a) contributions from Carbon-14 free matrix due to continuous recrystallization of carbon dioxide (CO_2) and calcium (Ca) assessed using cation concentrations, and (b) Carbon-14 dissolved inorganic carbon ($^{14}C_{DIC}$) that exchanged with carbon dioxide (CO_2) in the soil and the carbonate matrix. The Carbon-13 (^{13}C) isotope model and that of the matrix exchange considers both open and closed system carbonate reactions that are more realistic to carbonate reactions in nature. Clark and Fritz (1997) discuss limitations and applicability of these models in more detail.

The corrected ages of the waters from the sampled wells and the springs using the above correction methods are presented in Table 9. The statistical and the alkalinity models assume simplified carbonate evolution with little carbonate reactions resulting in a lower dilution of Carbon-14. This results in ages that are closer to uncorrected ages. Carbon-13 ($\delta^{13}C$) mixing model is highly dependent on the pH of the recharge water. When pH is varied from six to seven, it can result in differences in ages by about 50 percent. When dealing with paleogroundwater, it is nearly impossible to estimate pH that existed during recharge. The matrix exchange model includes both carbonate dissolution and exchange, and does not require specified input parameters. Therefore, the corrected ages from matrix-exchange model may prove to be better estimates for the actual ages of the waters.

Nearly all of the models considered show negative ages for well samples 3 and 11 indicating that the ages for these waters were overcorrected to the future (Table 9). These samples have high Tritium and Carbon-14 percent modern Carbon values indicating contribution from modern to sub-modern waters.

3.3.3.2.4 SULFUR-34 ($\delta^{34}S$) ISOTOPES

Sulfur compounds in the subsurface can occur in the form of sulfate and sulfide minerals, dissolved sulfate, dissolved sulfide, and hydrogen sulfide gas. Sulfur compounds from these sources participate in the geochemical evolution of groundwater and contribute to groundwater salinization. Sulfur-34 is generally fractionated between sulfur compounds due to biological cycling. The standard used for reporting sulfur isotopes is the Canyon Diablo Troilite (CDT) meteorite. Values exceeding +20 parts per thousand CDT are found in association with evaporites and limestones. Permian anhydrite ($CaSO_4$) can have Sulfur-34 ($\delta^{34}S$) values in the range of 9.3 to 23 parts per thousand CDT (Thode and Monster, 1965). Negative Sulfur-34 values are formed under diagenetic conditions where reduced sulfur compounds are formed (Krouse, 1980). The dissolution of gypsum or anhydrite occurs without measurable isotopic fractionation; therefore, isotopic compositions of sulfate (SO_4) can be used as a tracer of the sulfate origin (Clark and Fritz, 1997). The Sulfur-34 ($\delta^{34}S_{SO4}$) values of the modern seawater have a composition of 21parts per thousand CDT.

Table 9. Corrected ages of the sampled waters using selected adjustment models (Chowdhury and others, 2004b).

Sample Well ID	State Well Number	Measured ^{14}C DIC (pmc)	Unadjusted age* (^{14}C years)	Selected adjustment models			
				Statistical[1] (Vogel, 1970)	Alkalinity[2] (Tamers, 1975)	^{13}C Mixing model[3] (Pearson and Hanshaw, 1970)	Matrix-exchange[4] (Fontes and Garnier, 1981)
1	5202405	11.2	17,580	15,150	12,368	13,117	9,766
2	5201302	24.5	11,290	8,679	5,897	6,566	5,713
3	5202404	71.7	2,670	-198	-2,980	685	-2,256
4	5209501	33.3	8,830	6,142	3,360	7,513	4,392
5	5202611	14.8	15,360	12,846	10,064	10,733	10,918
6	4752602	9.2	19,200	16,776	13,995	14,252	14,190
7	4758505	10.7	17,950	15,528	12,746	12,832	10,896
8	5209303	24.2	11,410	8,781	5,999	7,721	5,569
9	5138803	16.2	14,630	12,099	9,317	10,678	8,450
10	4764401	28.01	10,220	7,572	4,790	5,539	5,165
11	4748701	58.89	4,250	1,429	-1,353	-293	-813
12	4759603	11.83	17,140	14,698	11,916	11,651	11,851
13	4718402	12.09	16,970	14,518	11,736	13,458	11,969
14	4755802	11.05	17,690	15,261	12,480	14,411	15,515
17	4717302	13.49	16,090	13,612	10,830	12,481	10,597

*Unadjusted age calculated using A_0 of 100 pmc and ^{14}C half life of 5,730 years

[1] ^{14}C remaining after dilution 0.7, median value for Karst Systems

[2] ^{14}C remaining is 0.5 percent as per carbonic acid dissolution of limestone

[3] pH = 7, enrichment for $^{13}C_{DIC\text{-}CO2\ (soil)} = 6$

[4] ^{13}C of matrix carbonates = 3, $^{13}C_{soil\text{-}CO2} = 21$, and enrichment $^{13}C_{CO2\text{-}CaCO3} = -11.8$

We have analyzed for Sulfur-34 ($\delta^{34}S_{SO4}$) of Phantom Lake Spring, San Solomon Springs, and the groundwater from wells west and northwest of the springs. We observed that the Sulfur-34 ($\delta^{34}S_{SO4}$) values of Phantom Lake Spring, San Solomon Springs, and sample 15 have identical values (10 to 10.6 parts per thousand CDT). Samples 6, 16, and 17 have nearly identical values (approximately 11 parts per thousand CDT). Sample 14 has a Sulfur-34 ($\delta^{34}S_{SO4}$) value of 3.2 parts per thousand CDT and sample 7 has a value of 8.2 parts per thousand CDT. Most of the Sulfur-34 ($\delta^{34}S_{SO4}$) values indicate that they are derived from dissolution of Permian evaporites bearing characteristic values. Samples 7 and 14 show slight depletion due to biogenic sulfate reduction.

3.3.4 Geochemical Modeling Results

Model runs involved speciation of the different elements, determining their saturation states, and exploring various mixing and dissolution/precipitation reactions.

Saturation indices (SI) refer to the saturation states of the water with respect to a given mineral phase (Table10) (Plummer and others, 1996). A mineral precipitates from the water if it is saturated (SI greater than 0) and dissolves when under-saturated (SI less than 0). Saturation states of the waters with respect to the different mineral phases are presented in Table 10. Only four samples are saturated with respect to calcite, but the remainder of the samples are under near-saturation (less than -0.3) except for samples 3, 4, 8, and 10. Samples 3, 4, 8, and 10 are also considerably under-saturated with respect to the rest of the minerals reported in Table 10. This level of under-saturation with respect to all mineral phases perhaps indicates that the waters were derived from recent recharge events. Most of the samples are also under near-saturation with respect to aragonite and dolomite, and only two samples (12 and 17) show near-saturation with respect to gypsum. Although one sample (16) is over-saturated with respect to fluorite, several samples (1, 5, 7, 9, 12, and 17) show near-saturation.

Table 10. Saturation states of the waters with respect to different mineral phases. Subscript SI refers to the saturation states of each mineral phases where SI= IAP/KT. IAP is ion activity product and KT is equilibrium constant.

Sample number	Well Number	$Calcite_{SI}$	$Aragonite_{SI}$	$Dolomite_{SI}$	$Gypsum_{SI}$	$Anhydrite_{SI}$	$Celestite_{SI}$	$Fluorite_{SI}$
1	5202405	-0.12	-0.26	-0.24	-0.92	-1.14	-0.91	-0.24
2	5201302	-0.29	-0.44	-0.75	-1.13	-1.35		-1.4
3	5202404	-0.42	-0.56	-1.56	-2.48	-2.7	-3.13	-1.6
4	5209501	-0.82	-0.97	-2.32	-3.07	-3.29		-0.92
5	5202611	-0.13	-0.27	-0.29	-0.76	-0.98	-0.81	-0.44
6	4752602	-0.19	-0.34	-0.32	-0.82	-1.04	-0.83	-0.67
7	4758505	0.016	-0.13	-0.001	-0.91	-1.14	-1.86	-0.22
8	5209303	-0.91	-1.05	-1.84	-2.19	-2.41	-1.93	-2.27
9	5138803	0.005	-0.14	-0.79	-1.52	-1.74	-2.45	-0.1
10	4764401	-0.86	-1	-1.82	-2.54	-2.75	-1.64	-1.2
11	4748701	-0.15	-0.29	-0.38	-1.01	-1.234	-0.54	-0.56
12	4759603	0.13	-0.014	-0.05	-0.22	-0.44	-0.66	-0.4
13	4718402	-0.2	-0.34	-0.27	-0.97	-1.19	-0.96	-1.28
14	4755802	-0.04	-0.18	-0.07	-0.97	-1.19	-0.63	-0.83
15	4755401	0.09	-0.05	0.37	-0.86	-1.08		-0.61
16	4726101	-0.035	-0.179	-0.31	-0.68	-0.91	-1.15	0.06
17	4717302	-0.17	-0.31	-0.57	-0.29	-0.51		-0.27

We made several scenario runs using NETPATH where we changed the source areas assuming:

(1) **A northwest to southeast flow path**: the spring waters are derived from areas as far as the northwest limit of our sample sites (near Beacon, along the northwest Culberson/Hudspeth county line) through the Apache Mountains and the source water mixes as it flows east towards the springs including receiving potential recharge from the Davis Mountains (flow path following locations of the wells 17, 16, 6, 14, 8, and 1);

(2) **A northwest and west to southeast flow path**: the spring waters are derived from areas as far as the northwest limit of our sample sites (near Beacon, along northwest Culberson/Hudspeth county line) and the source water mixes with groundwater from Wild Horse Flats and the Apache Mountains and flows east towards the springs (flow path follows locations of the wells 17, 6, 12, 14, 10 and 1); and

(3) **A west to southeast flow path**: the spring waters are derived from areas around the Wild Horse Flats through the Apache Mountains and the source water mixes as it flows east towards the springs including receiving potential recharge from the Davis Mountains (flow path following locations of the wells 12, 6, 14, 10, 8, and 1).

We used the same ion, isotopic, and phase constraints in all the above simulations. We used calcium (Ca), Carbon-13 (^{13}C), Carbon-14, Sulfur-34, calcite, and gypsum as constraints unless otherwise stated. We allowed dissolution and precipitation of both calcite and gypsum. We assumed current chemical conditions at Phantom Lake Spring, which reflects more of a regional base flow scenario since the existing drought has limited local contributions from the Davis Mountains.

3.3.4.1 Northwest to southeast flow path (17, 16, 6, 14, 8, and 1)

Results from this simulation indicate that the final water chemistry in the Phantom Lake Spring can potentially be matched if the source water was comprised of 10 percent from well 17; 4 percent from well 16; 41percent from well 6; 31 percent from well 14; and13 percent from well 8 in the Davis Mountains (Table 11). Under this scenario, the waters are close to saturation with respect to calcite and dolomite. The user-defined equation uses measured Carbon-14 percent modern Carbon values in wells where the data is available.

This simulation includes all the components of groundwater from the Delaware, Apache, and Davis mountains. The computed isotope values closely match the measured values of the Phantom Lake Spring water. We believe that source of the spring waters are derived along this general flow path. Additional research may be needed to further define the complete source area.

3.3.4.2 Northwest and west to southeast flow path (17, 6, 12, 14, 10, and 1)

Simulation along wells 17, 6, 12, 14, 10, and 1 indicate 7 percent water from well 17; 5 percent from well 6; 45 percent from well 12; 34 percent from well 14; and 9 percent from well 10 (Table 12). Under this scenario, the waters are close to saturation with respect to calcite and gypsum. The user-defined equation uses measured Carbon-14 percent modern Carbon values in wells where the data is available.

3.3.4.3 West to southeast flow path (12, 6, 14, 10, 8, and 1)

Simulation along wells 12, 6, 14, 10, 8, and 1 with a predominance of compositional control from waters in the Wild Horse Flats indicate 5 percent water from well 12; 61 percent from well 6; 26 percent from well 14; 8 percent from well 10; and nothing from well 8 (Table 13). Under this scenario, the

waters are close to saturation with respect to calcite and gypsum. The user-defined equation uses measured Carbon-14 percent modern Carbon values in wells where the data is available. There are also considerable differences between the measured and computed isotope values.

Table 11. NETPATH model output for northwest to southeast scenario.

Model 1

Source Water	Percent Contribution
Well 17	0.10
Well 16	0.04
Well 6	0.41
Well 14	0.31
Well 8	0.13

Calcite (SI)	0
Dolomite (SI)	0

Model Parameters	Computed	Observed
C-13[1]	-7.71	-7.4
C-14 (percent modern)[2]	11.6	11.2
Sulfur-34[3]	9.25	10.6

1 - C-13 ratios in units per mil with respect to PDB standard
2 - C-14 is activity in percent modern.
3 - S-34 ratios in units per mil with respect to CDT standard.

Model	Ao (initial Ao)	Computed (initial)	Observed (no decay)	Age (final)
Original data	11.67	11.67	11.20	340
Vogel	85.00	85.00	11.20	16,754
Tamers	59.84	57.79	11.20	13,565
User Defined	100.00	100.00	11.20	18,098

Table 12. NETPATH model output for northwest and west to southeast scenario.

Model 2

Source Water	Percent Contribution
Well 17	0.074
Well 6	0.05
Well 12	0.45
Well 14	0.34
Well 10	0.09

Calcite (SI)	0
Gypsum (SI)	0

Model Parameters	Computed	Observed
C-13[1]	-7.52	-7.4
C-14 (percent modern)[2]	11.33	11.2
Sulfur-34[3]	9.27	10.6

1 - C-13 ratios in units per mil with respect to PDB standard
2 - C-14 is activity in percent modern.
3 - S-34 ratios in units per mil with respect to CDT standard.

Model	Ao (initial Ao)	Computed (initial)	Observed (no decay)	Age (final)
Original data	11.38	11.38	11.20	130
Vogel	85.00	85.00	11.20	16,754
Tamers	59.94	59.89	11.20	13,859
Ingerson and Pearson	5.00	5.00	11.20	-6,667
Fontes and Garnier	2.83	2.83	11.20	-11,372
User Defined	11.34	11.34	11.20	101

Table 13. NETPATH model results for west to southeast scenario.

Model 3

Source Water	Percent Contribution
Well 12	0.05
Well 6	0.61
Well 14	0.26
Well 10	0.08
Well 8	0

Calcite (SI)	0
Gypsum (SI)	0.09

Model Parameters	Computed	Observed
C-13[1]	-7.51	-7.4
C-14 (percent modern)[2]	16.24	11.2
Sulfur-34[3]	5.69	10.6

1 - C-13 ratios in units per mil with respect to PDB standard
2 - C-14 is activity in percent modern.
3 - S-34 ratios in units per mil with respect to CDT standard.

Model	Ao (initial Ao)	Computed (initial)	Observed (no decay)	Age (final)
Original data	11.37	11.37	11.20	122
Mass Balance	71.57	71.57	11.20	15,333
Vogel	85.00	85.00	11.20	16,754
Tamers	59.84	59.84	11.20	13,853
Ingerson and Pearson	5.00	5.00	11.20	-6,667
Fontes and Garnier	2.83	2.83	11.20	-11,367
User Defined	16.24	16.24	11.20	3,072

3.3.4.4 Davis Mountains storm flow

In addition to making the above runs, we made a simulation run taking into consideration water composition in Phantom Lake Spring during 1932 when considerable increases in flow was observed after heavy rain events causing flash floods (White and others, 1941). In this simulation run, we considered wells 3, 14, and 1 (Table 14). We observed that 5 percent of water from well 14 and 95 percent from well 3 (representing Davis Mountains water chemistry) is necessary to reach water composition in Phantom Lake Spring when fresh water from flash flood reaches the spring. In this solution, calcite dissolves in the water and the water requires dilution. Because no Carbon-14 data were available for the storm flow component, we assumed a Carbon-14 value for this water based on their observed arrival within hours of heavy rains into the springs. Given that the water will be mixed with the component from the west, we assumed a slightly lower Carbon-14 percent modern Carbon (60 percent modern Carbon) value for this storm flow component. The adjusted Carbon-14 ages in years in this simulation using the storm flow component indicate that water from the Davis Mountains can readily reach the springs. We were unable to generate any model when we considered the diluted spring water in the Phantom Lake and included water samples from wells located west of the Delaware Mountains and west of the Apache Mountains.

We did not report the adjusted Carbon-14 ages (travel time) for the first three simulations as there were many mixing points along the hypothesized flow path. In NETPATH, groundwater inputs with varying Carbon-14 signatures along the flow path are averaged and treated as an initial value based on carbon mass transfer between sinks and sources. Thus, the adjusted model will not provide an accurate travel time. In order to estimate the travel time between potential source areas in the Delaware Mountains and the springs, we selected only two wells (wells 17 and 1) and allowed no mixing to occur (Table 15). We observed that this solution requires calcite precipitation and dilution of the waters.

The adjusted Carbon-14 ages of the water from our sampling site west of the Delaware Mountains area yielded 1,579 years. If this travel time is correct, then the flow rate is about 0.75 feet per day, reasonable for a Karst terrain.

If these flow rates are accurate, water issuing from the springs were derived long ago during the Pleistocene era and may not quickly be replenished. The model results are very sensitive to values assumed for Carbon-14 and Carbon-13 isotopes in the initial solution. Also initial Carbon-14 activity values chosen by the different models produce variable ages. In addition, there are some differences between the computed and the measured isotope values indicating that the modeling solution may not have been exactly reproduced. The travel time is added to the initial water to calculate the ages of the final spring water. In general, we favor the ages (about 13,000 to 17,000 years) in the NETPATH results provided by Tamers (1975) and Vogel (1970) models, as they are more consistent with the expected ages of the waters although they use simplified solution. Given the uncertainty of the assumptions, we feel that the modeling solution is non-unique and may produce variable results. However, the variable results are unlikely to change the overall conclusion.

Table 14. NETPATH results for Davis Mountains scenario.

Model 4

Source Water	Percent Contribution
Well 3	0.95
Well 14	0.05
Calcite (SI)	0
Gypsum (SI)	0.09
Calcite (SI)	2.48
Gypsum (SI)	0
Dilution Factor	1.07

Model Parameters	Computed	Observed
C-13[1]	-9.86	-7.4
C-14 (percent modern)[2]	60.00	11.2
Sulfur-34[3]	2.10	10.6

1 - C-13 ratios in units per mil with respect to PDB standard
2 - C-14 is activity in percent modern.
3 - S-34 ratios in units per mil with respect to CDT standard.

Adjusted C-14 age in years: 0* * = based on user-defined.

Model	Ao (initial Ao)	Computed (initial)	Observed (no decay)	Age (final)
Original data	66.91	64.04	60.00	539
Mass Balance	60.30	57.71	60.00	-322
Vogel	85.00	81.35	60.00	2,517
Tamers	63.43	60.73	60.00	100
Ingerson and Pearson	52.76	50.50	60.00	-1,426
Fontes and Garnier	52.33	50.09	60.00	-1,492
Eichinger	45.34	43.39	60.00	-2,679
User Defined	66.91	64.04	60.00	539

Table 15. NETPATH results for estimating age of spring waters.

Model 5

Calcite (SI)	-5.12
Dilution factor:	1.49

Model Parameters	Computed	Observed
C-13[1]	-6.15	-7.4
C-14 (percent modern)[2]	13.55	11.2
Sulfur-34[3]	11	10.6

1 - C-13 ratios in units per mil with respect to PDB standard
2 - C-14 is activity in percent modern.
3 - S-34 ratios in units per mil with respect to CDT standard.

Adjusted C-14 age in years: 1,579* *= based on user-defined.

Model	Ao (initial Ao)	Computed (initial)	Observed (no decay)	Age (final)
Original data	13.49	13.56	11.20	1,579
Vogel	85.00	85.42	11.20	16,795
Tamers	57.27	57.56	11.20	13,531
Ingerson and Pearson	34.40	34.57	11.20	9,317
Fontes and Garnier	33.50	33.66	11.20	9,098
Eichinger	28.78	28.92	11.20	7,842
User-defined	13.49	13.56	11.20	1,579

3.4 Aquifer Characterization (Physical Properties)

Aquifer characterization is the process of quantifying the physical features of an aquifer that control groundwater movement in the subsurface. Understanding the structural geology, the composition of the material in the subsurface, and the physical properties of that material are fundamental steps in characterizing an aquifer.

3.4.1 Structural Geology

For understanding the structural geology of the region, we researched previous field studies and reports, verified geology and exposed structure in the field, and interpreted well logs. Due to the complexities and inter-relationships of the geologic formations in the study area due to faulting, dissolution, and fracturing, our goal was to provide a simplified interpretation encompassing the general trends observed.

The Salt Basin graben is located between the Permian Delaware Basin and the Guadalupe Mountains, and the Diablo plateau to the west (Figure 1). The Delaware Basin contains more than 20,000 feet of Paleozoic sediments and is bounded by the Capitan Reef rocks exposed in the Guadalupe Mountains, Sierra Diablo, and the Apache Mountains (Sharp, 1990). The reef trend continues into New Mexico and southeastward in the subsurface. Salt dissolution, extensional normal faulting, and Tertiary volcanism have been the three most important geological processes that led to the creation of the Toyah basin, the Babb and Victorio flexure zones, the Rounsaville syncline trend/Stocks fault, and the Davis Mountains (Sharp, 1990). The Stocks fault bounds the north-northeastern flank of the Apache Mountains (Sharp, 1990).

The eastern margin of the Salt Basin is intensely faulted with faulting parallel to the north trending basin boundaries (Figure 47). In the Rustler Hills, the fractures and fold axes have easterly trend and the faults on the west side of the Salt Basin are more confined (Sharp, 1990). Nielson and Sharp (1985) believe the Babb and the Victorio flexure zones created permeability barriers that controlled locations of the surface drainage systems and the alluvial fans.

The Permian age strata in the Trans-Pecos can be divided into three aquifer systems (Nielson and Sharp, 1980):

- A low permeability basinal aquifer system containing sediments of the Delaware Mountains Group (Castile and the Rustler Formations),
- A high permeability shelf-margin facies with transmissivities exceeding 16,000 feet squared per day (ft^2/day) consisting of the Capitan Reef and the underlying Goat Seep limestone, and
- A shelf facies aquifer controlled by fracture porosity.

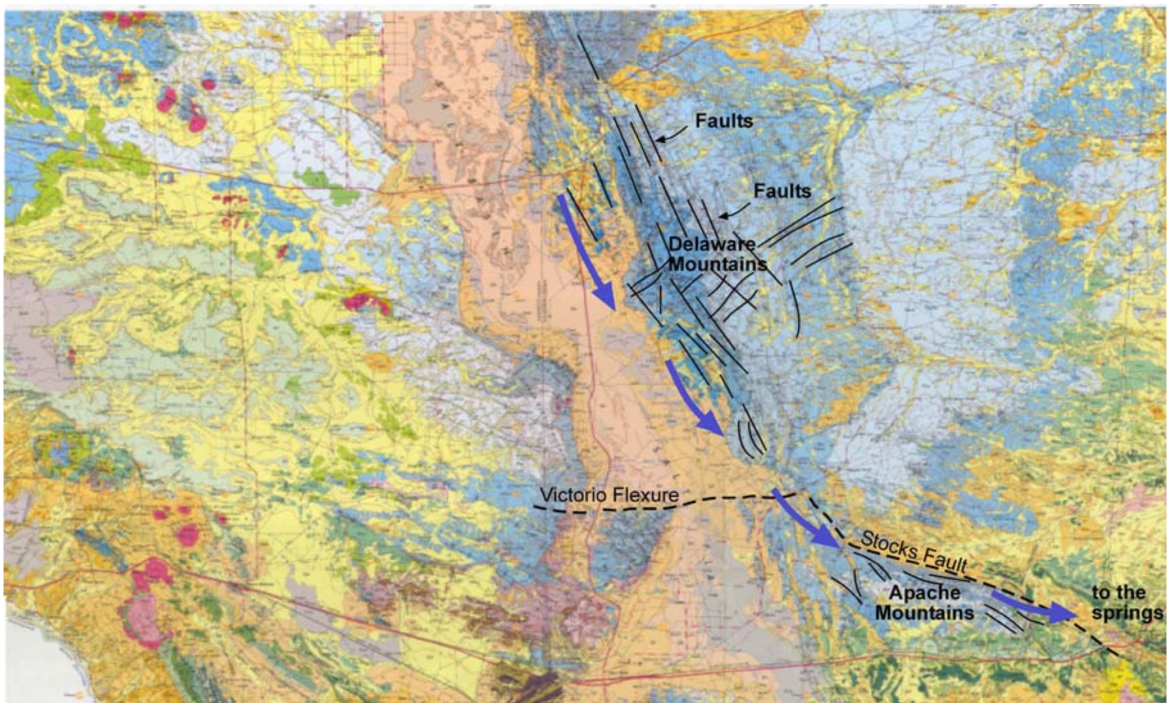


Figure 47. Map showing locations and orientations of faults in the study area adopted from the Geologic Atlas Maps of Texas (Bureau of Economic Geology, 1982 and 1985). Pink arrows show potential groundwater flow to the southeast along fractures near the Delaware Mountains. Blue arrows show west to east potential groundwater flow along fractures in the Apache Mountains. Springs are located farther southeast (not shown). Figure not to scale. Colors on the map represent rock types in the area (for descriptions see Bureau of Economic Geology, 1982 and 1985).

The rocks exposed around Balmorhea (Table 16) consist of Lower and Upper Cretaceous marine sediments, Tertiary volcanic deposits and lava flows, and Quaternary alluvial deposits (White and others, 1941). The Lower Cretaceous sediments consist of massive thick-bedded limestone with some minor inter-bedded calcareous shale and sandstone at the base. The Lower Cretaceous section thins towards the northwest and has a thickness of 500 feet near Balmorhea. The uppermost limestone exposed near the Phantom Lake spring contains several sinks or deep cavernous channels.

The Upper Cretaceous rocks are mainly composed of clay and are exposed beneath the lava on the steep front of the Davis Mountains and in the foothills. These rocks are 500 to 600 feet thick near Balmorhea. The Tertiary aged volcanics cap the Davis Mountains and numerous hills and ridges in Balmorhea. These volcanics have a total thickness of 1,500 to 2,000 feet and the basal unit is marked by a white tuff. Much of these rhyolitic lava flows are densely fractured and jointed and are exceedingly porous. The volcanics dip below the base of the stream gradient in structurally depressed areas where the lava may form a porous reservoir for the infiltrating rainfall as the base of the unit contains an impermeable tuff. Alluvium and gravel of Tertiary, Pliocene, and Recent age overlie the bedrock of the lower mountain slopes and most of the lowlands and are generally 15 to 25 feet deep.

Table 16. General stratigraphy of Reeves County (after Ogilbee and others, 1962).

ERA	SYSTEM	SERIES OR GROUP	STRATIGRAPHIC UNITS	MAXIMUM OBSERVED THICKNESSES (IN FEET)	DESCRIPTION
Cenozoic	Quaternary and Tertiary undifferentiated		Alluvium	1,550	Unconsolidated sand, gravel, silt, gypsum, clay, caliche, boulders, and conglomerates
	Tertiary		McCrutcheon Volcanic series	1,500-1,700	White tuff, ash, lava, breccia, with some sandstone, conglomerate, and fresh-water limestone
Mesozoic	Cretaceous	Gulf series	Rocks of younger Cretaceous age, undifferentiated	450 +/-	Clay, shale, marl, and limestone
			Boquillas flags	150 +/-	Thin-bedded, platy limestone with interbedded shale
		Comanche series Washita Group	Buda limestone	160	Limestone; locally contains a basal sand or conglomerate
			Boracho limestone	410	Limestone, marl, shale, and some sandstone
		Comanche series Fredericksburg group	Finlay limestone	40	Sandstone, arenaceous limestone, and coarse-grained massive limestone
			Cox sandstone	170	Sandstone, conglomerate, limestone, and silty marl
		Comanche series Trinity group	Yearwood Formation	180	Limestone, basal conglomerate
	Triassic	Dockum group	Santa Rosa sandstone	350	Reddish-brown and gray, medium to coarse, cross-bedded arkosic micaceous, and conglomeratic sandstone, cemented with calcite and silica and interbedded with red and green shale and siltstone
			Tecovas Formation	70	Red shale, siltstone, and very fine-grained sandstone
Paleozoic	Permian	Ochoa series	Dewey Lake red beds	525	Red siltstone cemented with gypsum and calcite
			Rustler Formation	520	Dolomite, anhydrite, sandstone, conglomerate, and variegated shale. Locally contains halite and limestone
			Salado Formation	3,900	Mostly halite with subordinate amounts of anhydrite, and small amounts of sylvite, orange poly-halite, dolomite, and magnesite
			Castile Formation		Mostly calcareous anhydrite, some beds of halite and associated salts
		Guadalupe series Delaware Mountain group			Sandstone, limestone, and shale

Based on Bulletin 6214 Table 2

3.4.1.1 Field Verification

Using the geologic map and geologic cross-section from the, "Groundwater Resources of the Balmorhea Area in Western Texas" report (White and others, 1941), we documented the orientation and dip of the faults located in the immediate area of the springs around Balmorhea, Texas.

The beds of finely bedded tuffs are dipping at 80 to 90 degrees because of drag folding along the fault. The tuffs are within the Huelster Formation, which underlies the Star Mountain rhyolite. The tuffs identified were thin with layers up to two inches thick, reddish-brown to brown, with white calcareous laminae. We located a similar fault to the southwest of Brogada Hills, closer to the city of Balmorhea and northeast of East Sandia Springs. The fault located down dip from East Sandia Springs appears to act as a barrier to groundwater flow.

After finishing the surveys along and on both sides of the faults near San Solomon and East Sandia Springs, we completed a series of traverses along the ridge above Phantom Lake Spring. This provided an opportunity to observe the orientation, distribution, density, and predominant direction of fractures on the ridge. In addition, we looked for the presence of one or more faults bounding the ridge, which could explain the flow patterns of the springs.

We located fractures in numerous outcrops along the drainages on the northeast side of the ridge. The primary fracture direction is north 45 degrees east. The principal orientation of the fractures is vertical to the outcrop surface. The beds are dipping at about 12 degrees to the northwest. Fracture density varied with some zones having two to three fractures per foot to zones with fracture separation of several feet. Fracture density increased near the fault. We identified the location of the fault by the presence of Boquillas Limestone at the base of the ridge. The ridge is composed of Buda Limestone.

The Buda Limestone, which is Lower Cretaceous, is thin to thick bedded, fine-grained, and very hard in the upper 40 feet. The middle Buda Limestone is about 60 feet of argillaceous limestone that is thinly- to thickly- bedded. The lower Buda Limestone, which is not exposed on the ridge, is a 40-foot unit of bioclastic, coquinoid limestone. The Boquillas Formation, in contrast, is Upper Cretaceous and consists of granular limestone in thin, mostly cross-laminated beds interbedded with light yellowish gray to grayish orange siltstone. The Boquillas Formation is probably less than a hundred feet thick.

Based on the stratigraphy of the combined Buda and Boquillas sections, we estimate the fault displacement at about 200 to 250 feet to the northeast with a strike of north 40 degrees west. It also should be noted that the fault parallels the main passage in the cave at Phantom Lake Spring.

3.4.1.2 Well Log Interpretation

We located eleven logs from Jeff Davis County: two electric logs and nine driller's logs. Reeves County had 44 logs: 14 electric logs and 30 driller's logs. Culberson County had 25 logs: four electric logs and 21 driller's logs.

3.4.1.2.1 BALMORHEA AREA

We developed a cross-section using Autodesk Map™, driller logs, and data collected in the field for the localized area around the springs (Figures 48 and 49). The springs in the system issue from the contact between the Buda Formation and the underlying Boracho Formation. In the case of San Solomon, Giffin, and East Sandia springs, groundwater collects in pools that form from within the alluvium found at the surface (Figure 49).

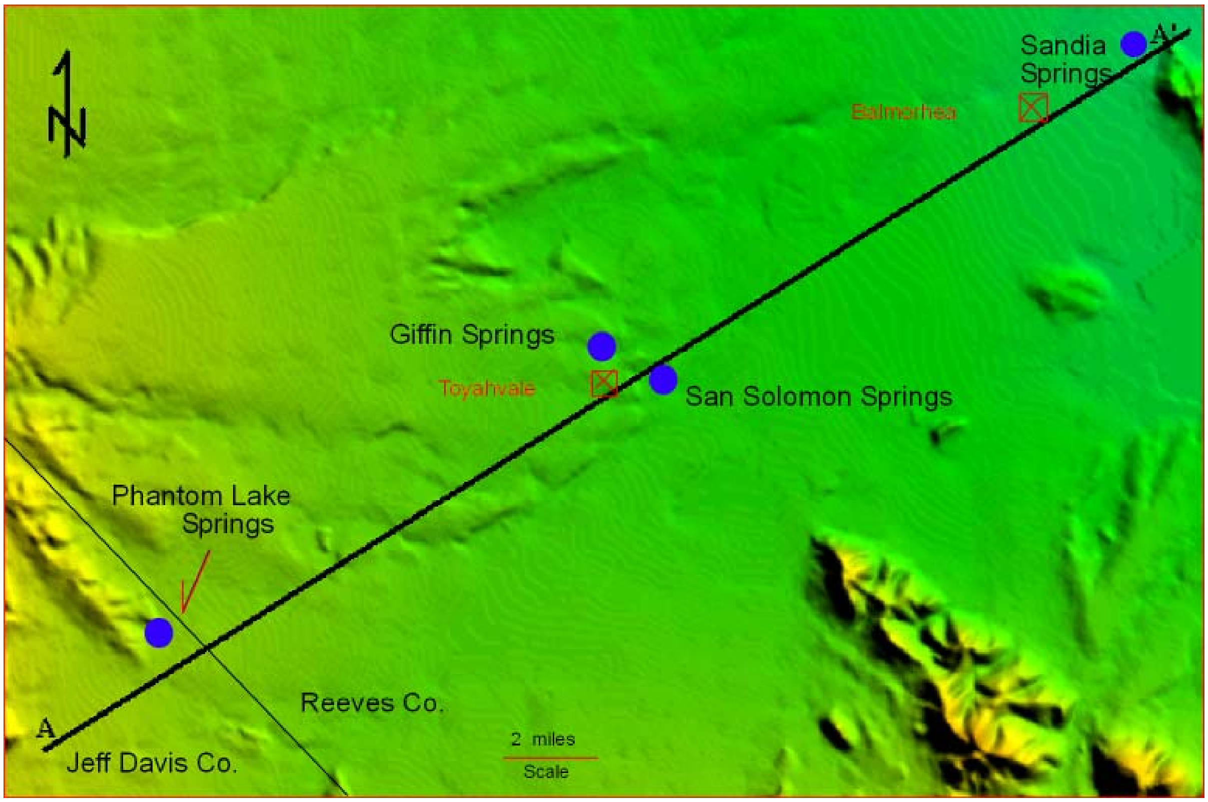


Figure 48. Location of cross-section extending from Phantom Lake Spring to East Sandia Springs.

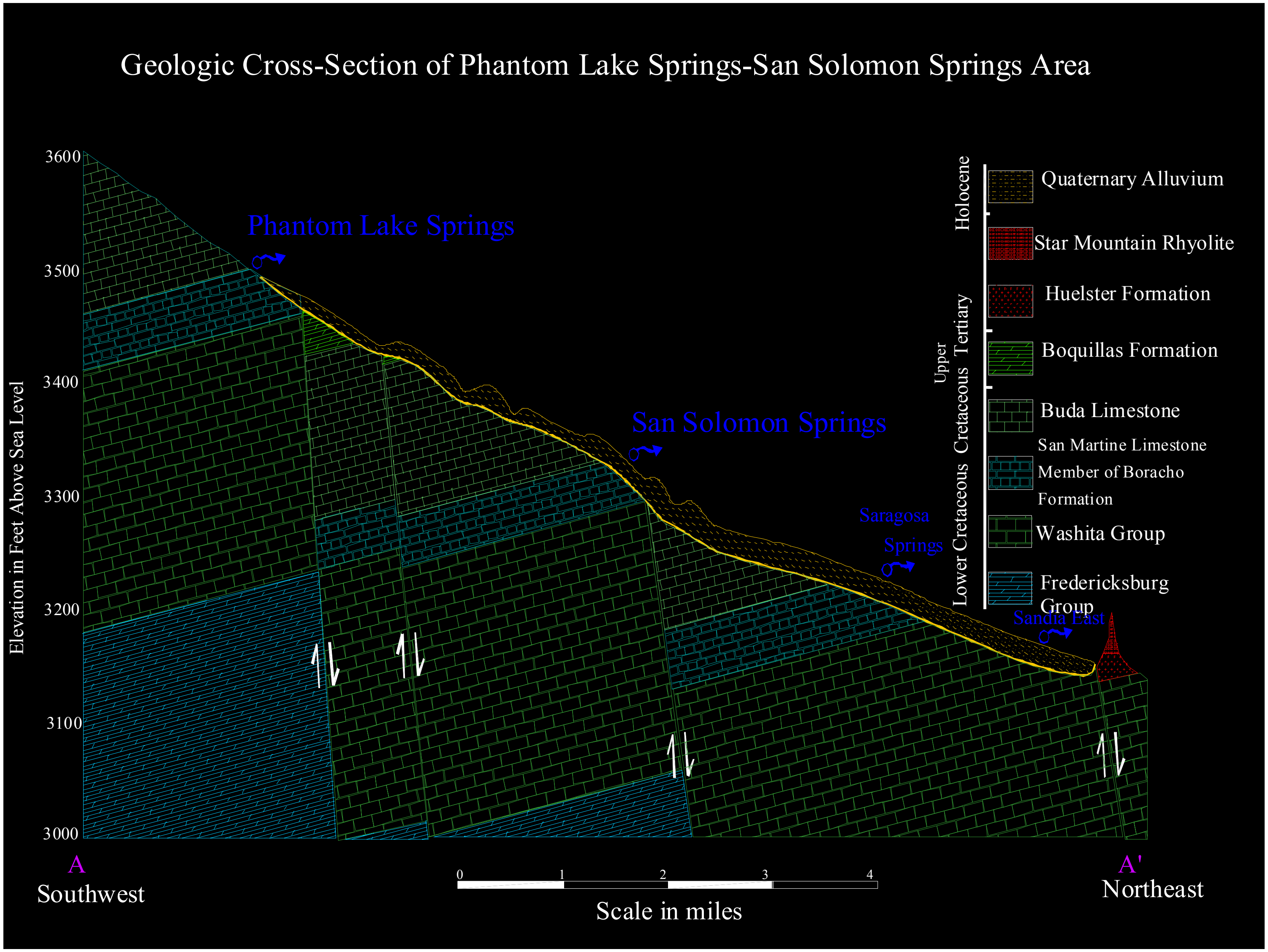


Figure 49. Geologic cross-section of the San Solomon Springs area.

To examine the influence of faulting on the localized groundwater flow, we first generated a potentiometric map of the spring discharge area using a kriging method in Surfer 7.0 with water-level measurements extracted from our groundwater database (Figure 50). The resulting map shows a general slope from the edge of the basin with water flowing from the southwest to the northeast.

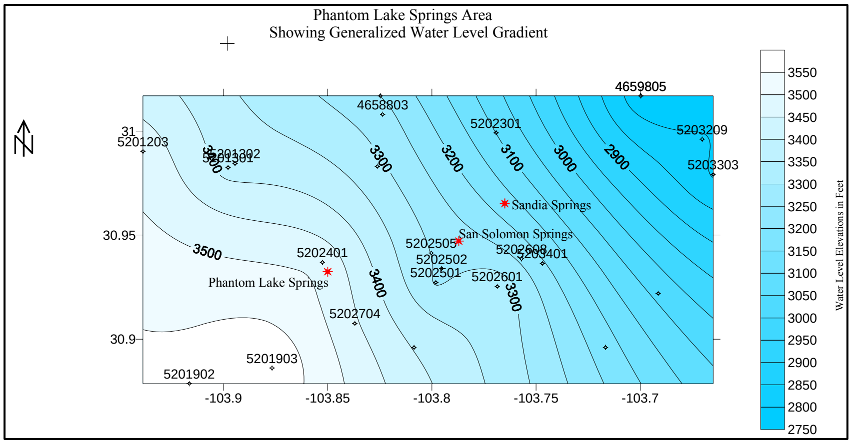


Figure 50. Generalized potentiometric map of San Solomon Springs system discharge area.

We then added in hypothesized faults from data gathered in the field to examine the possible influence of faulting upon flow patterns (Figure 51). The implications from this analysis suggest the faults may influence the rate of flow through the area and to a small degree the flow patterns. This may explain the slight differences in water chemistry when we compare East Sandia Springs to the other springs in the system. The faults impede but do not retard flow up dip from East Sandia Springs. Groundwater becomes more saturated as it flows from the southwest to the northeast. This is substantiated by the higher conductivity (Figure 28) and lower temperatures (Figure 29) measured in East Sandia Springs. This also helps to explain why flow in Phantom Lake Spring increases considerably after 24 hours of heavy rainfall yet flow in the San Solomon and Giffin springs increases 48 hours after the same recharge event (Couch, 1978).

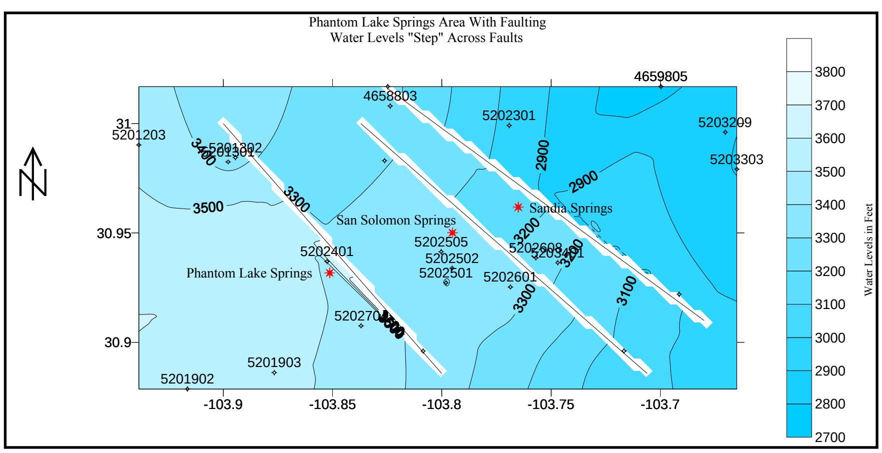


Figure 51. Potentiometric surface map with estimated lateral extent of faults from field measurements included showing one possible hypothesized affect of faults to the flow system in the discharge area.

3.4.1.2.2 REGIONAL AREA

We obtained preliminary structure data developed by LBG-Guyton and Associates for the West Texas Bolsons and Igneous aquifers groundwater availability models (GAM) to get a general understanding of the structural controls found within the region (Figure 52). As noted in C to C' the Wild Horse Flats of the Salt Bolson aquifer is isolated from aquifers to the south. Bolson deposits are deeper in the northern portion, which extends just to the northwest of the Apache Mountains in Culberson County. Wild Horse Flats cross-section D to D' indicates that the Salt Bolson is deeper in the western portion of the down-thrown graben than in the eastern portion.

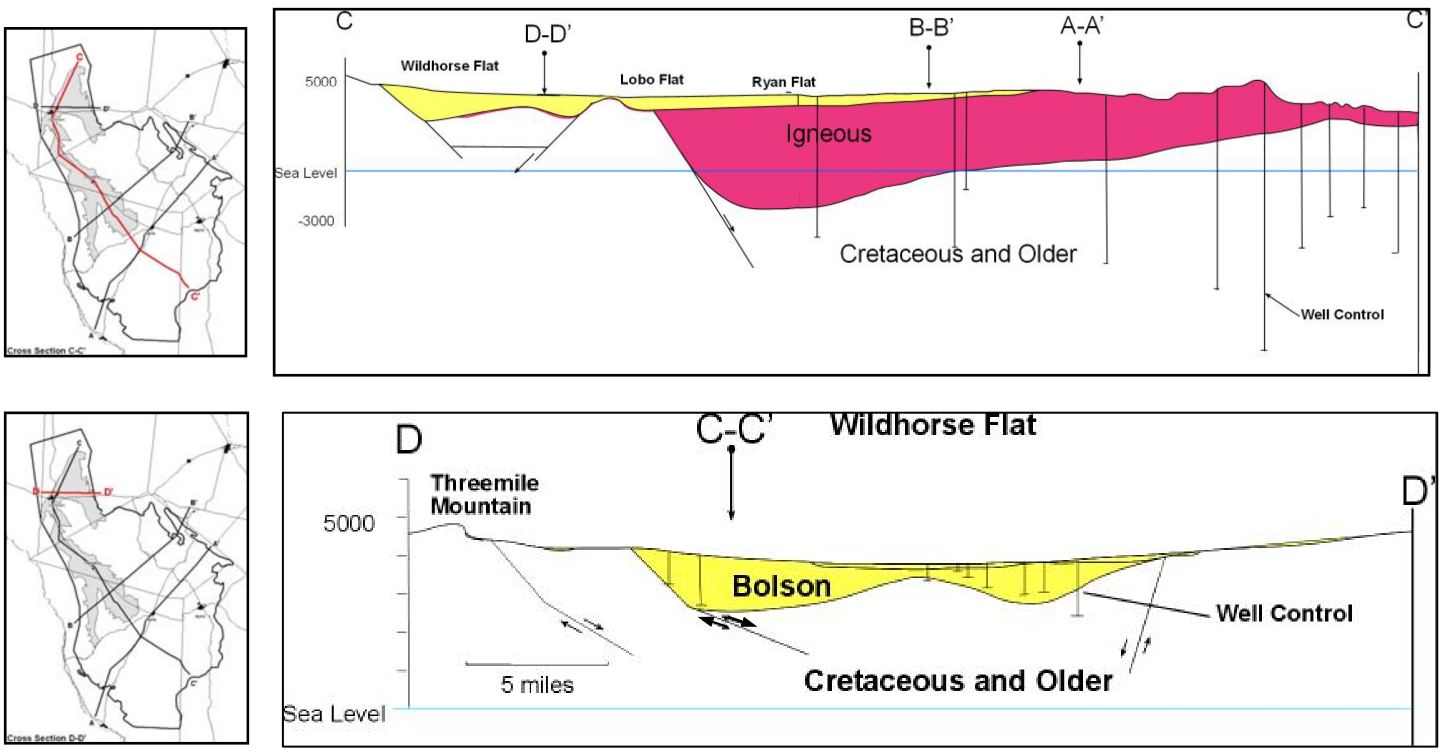


Figure 52. Preliminary regional cross-section from the Igneous and West Texas Bolsons groundwater availability model developed by LBG-Guyton and Associates (2004).

3.4.2 Pumping Tests

The results of our three single-well pumping tests are discussed in the following section. In addition to the aquifer tests, we researched and compiled additional information on the hydraulic properties of the surrounding aquifers.

3.4.2.1 Timber Mountain

On August 29, 2001, we conducted a short-term aquifer test on state well number 52-09-303. This well was located on the Timber Mountain Ranch in Jeff Davis County and completed in the Cretaceous. Analysis of the pumping test using the Theis, Theis Recovery, and Cooper Jacob (Figure 53) methods indicated a transmissivity in gallons per day per foot, (gpd/ft), of 383, 344, and 375, respectively. Specific capacity of the well during the test was 1.3 gallons per minute per foot of drawdown.

3.4.2.2 Jobe Ranch

On July 30, 2002, we conducted a short-term aquifer test on state well number 47-55-102, located on the Jobe Ranch in Culberson County. According to our groundwater database, completion of this well is in the Cretaceous System. The Neuman, Cooper Jacob, and Theis Recovery for the recovery portion of the test, methods were utilized for the analysis of the tests (Figure 54). The results indicate a transmissivity of 1,429; 2,884; and 1,712 gpd/ft, respectively. Specific capacity of the well during the test was 7.74 gallons per minute per foot of drawdown.

3.4.2.3 Huelster Well

On September 5, 2001, the owner of one of the long-term monitoring wells conducted a short-term pumping test. The Huelster Well, state well number 52-02-403, is located south-southeast of Phantom Lake Spring in Jeff Davis County and is completed in the Cenozoic Pecos Alluvium. With an assumed pumping rate of 500 gallons per minute (gpm), a transmissivity value of 4,448 gpd/ft was estimated (Figure 55).

3.4.2.4 Additional hydrologic properties

Hydraulic properties in the region vary considerably due to extensive faulting, depositional environment, and location (Figure 56 and Table 17). Wells with high transmissivity, greater than 10,000 feet squared per day, are completed either fully or partially in the Permian or Capitan Reef Formation. The highest transmissivity of the wells investigated was 80,000 feet squared per day. The average transmissivity value for wells completed entirely or partially in the Capitan Reef complex is around 20,000 feet squared per day. Comparatively, wells completed solely in the Salt Bolson have average transmissivity values of 3,400 feet squared per day while wells completed solely in the Cretaceous Formation have even lower average transmissivity values of 1,500 feet squared per day. Wells completed either fully or partially in the Delaware Mountain Group have average transmissivity values of 1,540 feet squared per day.

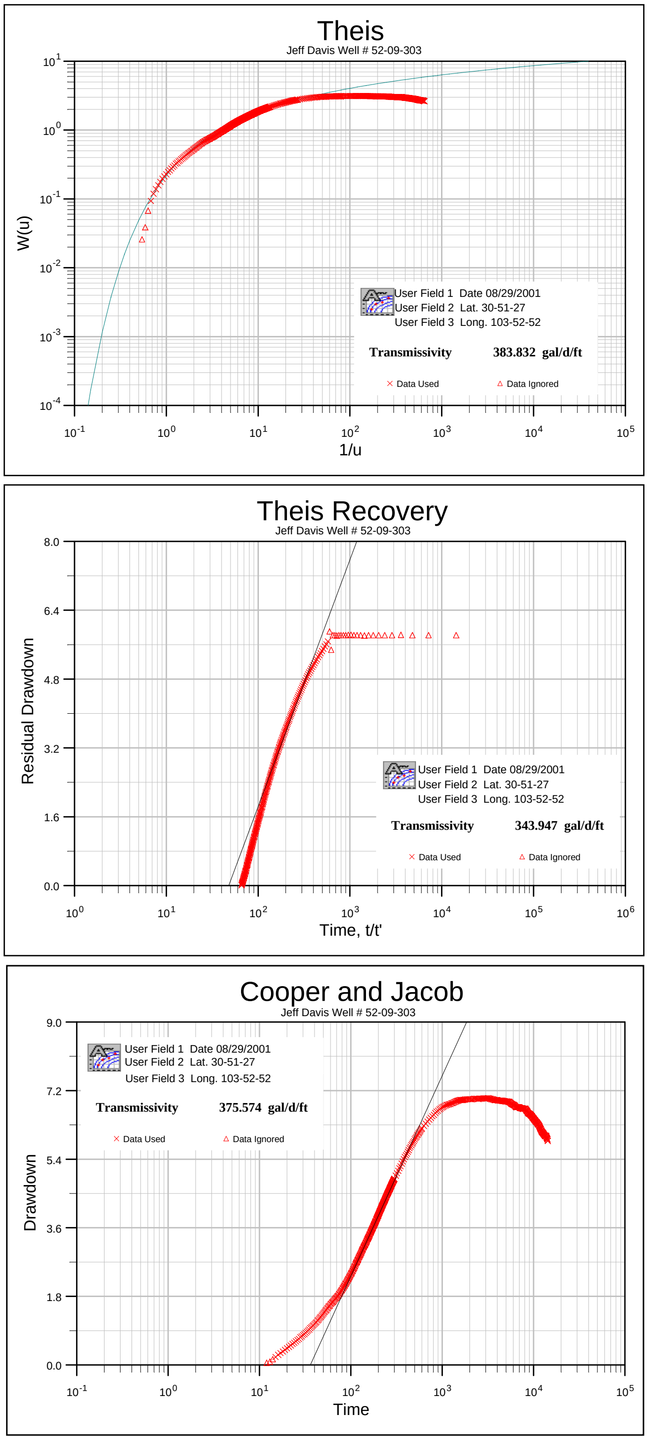


Figure 53. Timber mountain pump test analysis using Theis (Theis, 1935), Theis Recovery (Theis, 1935), and Cooper-Jacob (Cooper and Jacob, 1946)

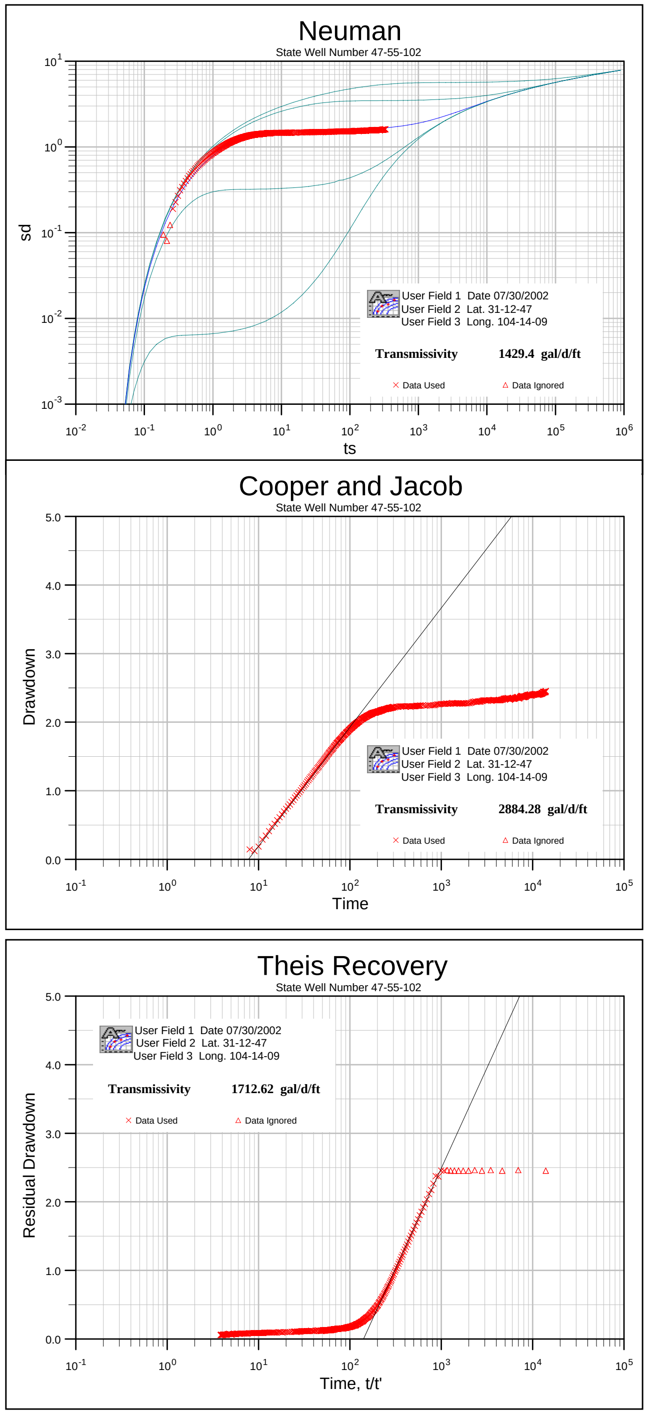


Figure 54. Jobe Ranch pump test using Neuman (Neuman, 1972), Cooper-Jacob (Cooper and Jacob, 1946), and Theis Recovery (Theis, 1935) method.

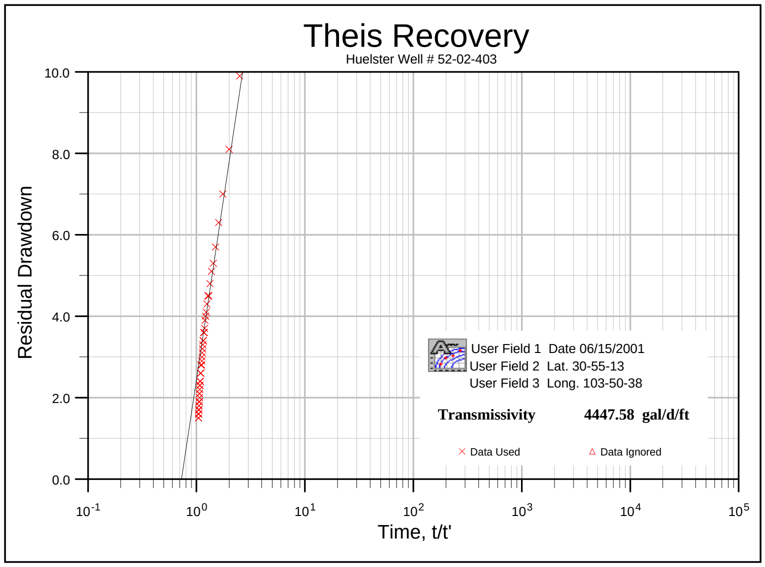


Figure 55. Theis recovery (Theis, 1935) analysis of Huelster monitoring well

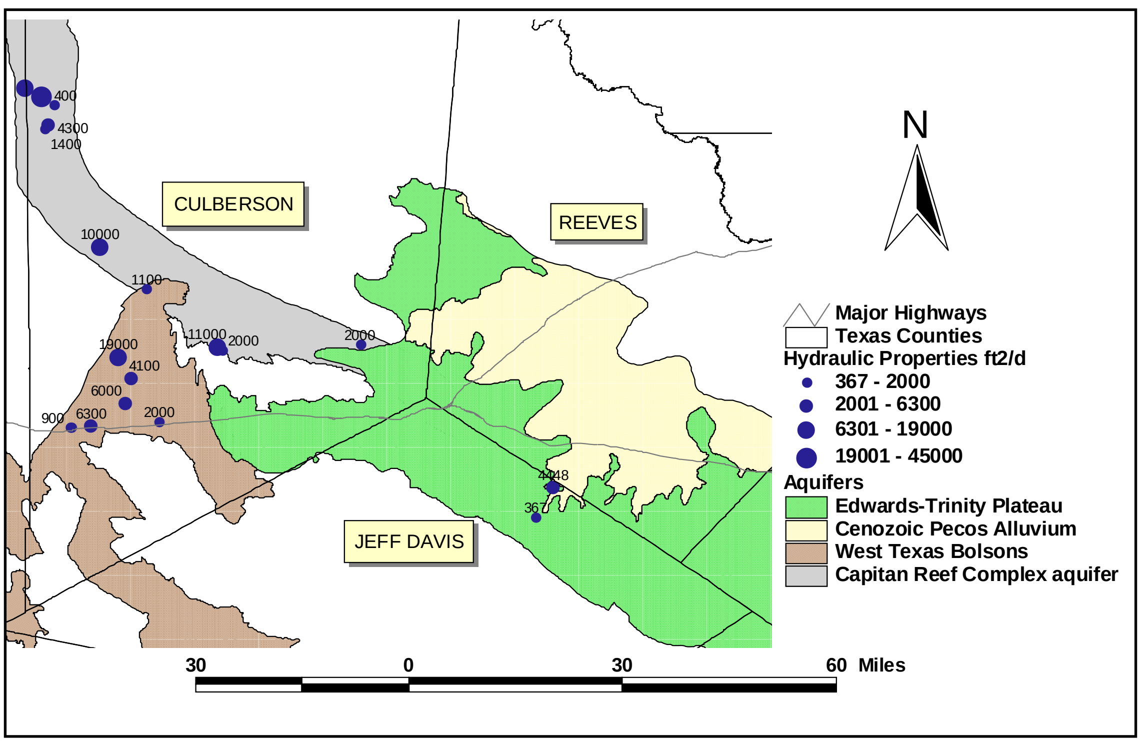


Figure 56. Locations of wells listed in Table17.

Table 17. List of wells and their associated hydraulic properties. *CSC is calculated from specific capacity and **AquiferTest was conducted during study.

AQUIFER	STATE WELL NUMBER	LOCATION	TRANSMISSITY ft^2/d	SOURCE
Capitan Reef Complex and Assoc. Limestones	4709207	Hudspeth Co. -Salt Flat	80,000	CSC*
Capitan Reef Complex and Assoc. Limestones	4717317	Culberson Co. -Salt Flat	11,000	Aquifer Test
Capitan Reef Complex and Assoc. Limestones	4752601	Culberson Co. –Wild Horse Flats	11,000	CSC*
Capitan Reef Complex and Assoc. Limestones	4734902	Culberson Co. –Wild Horse Flats	10,000	Aquifer Test
Capitan Reef Complex and Assoc. Limestones	4752602	Culberson Co. –Wild Horse Flats	2,000	Aquifer Test
Capitan Reef Complex and Assoc. Limestones	4752301	Culberson Co. –Wild Horse Flats	500	CSC*
Capitan Reef Complex & Delaware Mountain	4717321	Culberson Co. -Salt Flat	45,000	CSC*
Delaware Mountain Formation or Group	4743503	Culberson Co. –Wild Horse Flats	1,100	CSC*
Delaware Mountain Formation or Group	4718402	Culberson Co. -Salt Flat	400	Aquifer Test
Salt Bolson & Delaware Mountain Group	4718707	Culberson Co. -Salt Flat	4,300	CSC*
Salt Bolson & Delaware Mountain Group	4718404	Culberson Co. -Salt Flat	500	CSC*
Salt Bolson & Delaware Mountain Group	4717903	Culberson Co. -Salt Flat	1,400	Aquifer Test
Salt Bolson	4758602	Culberson Co. –Wild Horse Flats	5,000 to 6,300	Aquifer Test
Salt Bolson	4751807	Culberson Co. –Wild Horse Flats	4,100	CSC*
Salt Bolson	4758505	Culberson Co. –Wild Horse Flats	1,600	CSC*
Salt Bolson	4758502	Culberson Co. –Wild Horse Flats	900	CSC*
Salt Bolson & Capitan Reef	4717218	Hudspeth Co. -Salt Flat	2,500	CSC*
Salt Bolson & Permian Rocks	4751403	Culberson Co. –Wild Horse Flats	19,000	Aquifer Test
Salt Bolson & Cretaceous Rocks	4759102	Culberson Co. –Wild Horse Flats	6,000	Aquifer Test
Cretaceous Rocks	4759603	Culberson Co. –Wild Horse Flats	2,000	CSC*
Cretaceous Rocks	4755102	Culberson Co.- Apache Mountain region	2,000	Aquifer Test**
Cretaceous Rocks	5209303	Jeff Davis Co. – Davis Mountains region	367	Aquifer Test**
Alluvial Terrace & Channel Deposits	5202403	Jeff Davis Co. – Balmorhea area	4,448	Aquifer Test**

3.5 Water Budget

In order to investigate impacts to spring discharge, it is important to understand the water budget of the groundwater system. In this study we compiled, collected, and analyzed information on rainfall, pumping, and spring flow. The following sections discuss the results of our analysis.

3.5.1 Rainfall

Recharge occurs by rainfall that infiltrates through soil and rock to reach the saturated zone of the aquifer. For local recharge that initiates in the Davis Mountains and to the west in Culberson County, the factors that control recharge in the study area include (1) amount of precipitation and intensity, (2) location of drainages that concentrate surface-water runoff, (3) location and density of exposed fractured rocks, and (4) soil infiltration potential (LBG-Guyton Associates and others, 2001). Precipitation rates are generally greater at higher elevations. The perennial flowing creeks that drain Aguja, Little Aguja, Madera, and Cherry Canyons provide the avenue to transport and concentrate surface-water runoff (White and others, 1941). Groundwater recharge is more favorable in areas of higher elevation where fractured rocks are exposed. Water can enter the groundwater system directly through the exposed fractures and sinks or in areas where the creeks cross fractures zones. In lower elevations water transported in the creeks may enter the groundwater system though the gravels and terraces of the streambed (LBG-Guyton Associates and others, 2001).

White and others (1941) conducted a stream gain-loss study in the early 1930s during a period of significant rainfall. They installed stream gages on Madera, Little Aguja, and Aguja creeks at locations approximately 10 miles upstream from where they converge into Toyah Creek. The three gages had a total mountainous drainage area of approximately 153 square miles. The majority of stream flow was lost within a couple of miles downstream of the gauging sites and did not reach Toyah Creek. In addition, they monitored Cherry Creek, which is located up gradient from Phantom Lake Spring and has a mountainous drainage area of approximately 70 square miles. Water loss was observed in the streams in an area approximately three to six miles wide to the south of the Jeff Davis-Reeves county line in a zone that parallels the county line. It was hypothesized that local recharge to the springs only occurred when sufficient flow existed that allowed water to cross this zone and later enter the groundwater system closer to the discharge area through streambed infiltration.

For historical rainfall trends, we downloaded monthly precipitation data from information collected by the National Climate Data Center and compiled by Hydrosphere Data Products (2002). We plotted the total monthly and annual rainfall for the period of record for the Balmorhea, Mt. Locke, and Van Horn weather stations. For current trends, we compiled the hourly to quarter-hourly measurements into total monthly rainfall, plotted the results, and added a two-month moving average. We also compared the monthly data to the average monthly rainfall from the Balmorhea, Mt. Locke, and Van Horn stations.

3.5.1.1 Historical Rainfall

The Mt. Locke weather station (ID 416104) is located in Jeff Davis County (lat 30.42° N; long 104.01° W) to the southwest of the San Solomon Spring discharge area and has historical monthly precipitation totals from 1935 to 1999. The elevation of the weather station is 6,788.3 feet above sea level.

When monthly total rainfall is plotted (Figure 57), the wettest months on record occurred in early to mid summer months: 10.01 inches (August, 1966), 10.03 inches (August, 1968), 11.45 inches (July, 1976), 11.34 inches (June, 1984), and 10.62 inches (July, 1991). On average, monthly rainfall exceeds three inches per month in July, August, and September. The driest month, on average, occurs in March with less than 0.4 inches. Less than one inch of averaged monthly rainfall occurs in January, February, March, April, November, and December. The average monthly rainfall for the Mt Locke station is 1.64 inches per month.

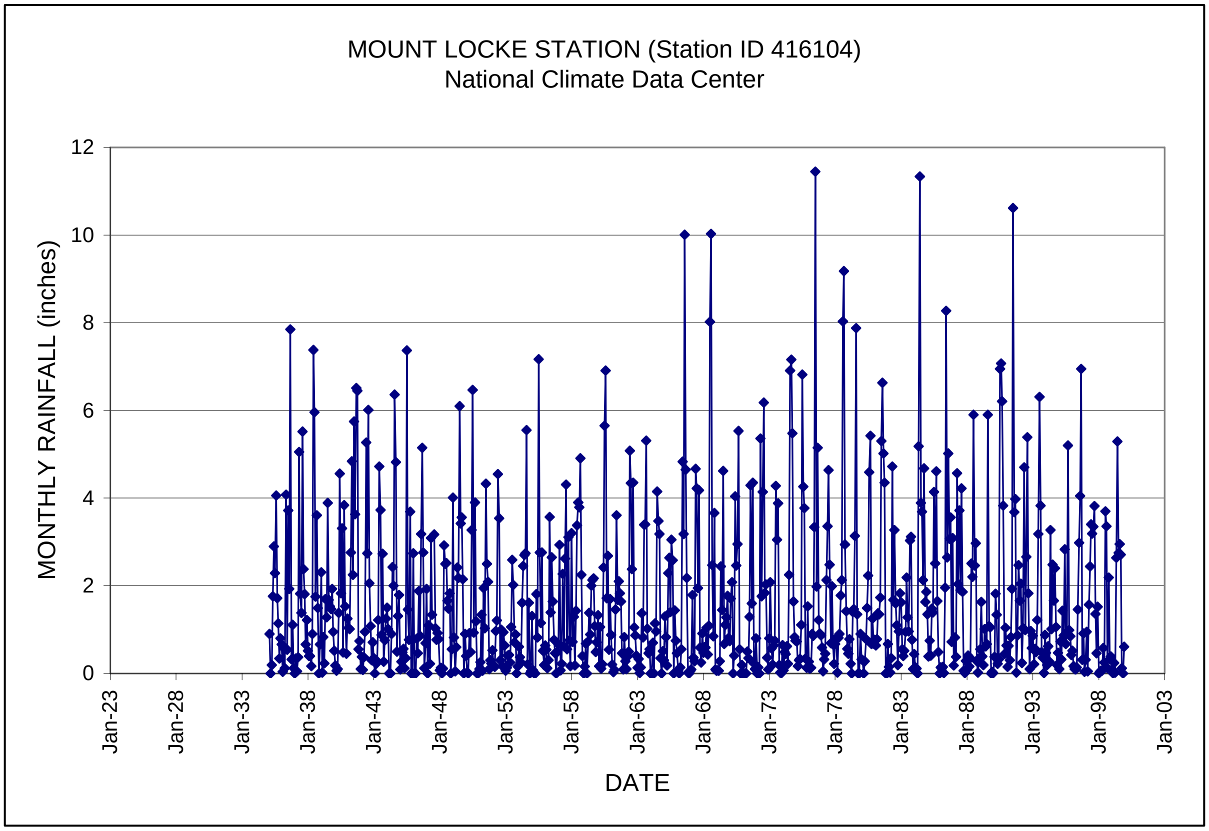


Figure 57. Monthly total rainfall reported in inches for Mt. Locke weather station.

When the data is summed annually (Figure 58), the average annual rainfall is 19.6 inches per year with a median value of 18.2 inches per year. The driest period on record occurred from 1950 to 1957, with an average annual rainfall of 15.29 inches per year. The next extended period of below average rainfall occurred from 1993 to 1996. The average annual rainfall during this period was 16.38 inches per year. The wettest year on record was in 1941 with an annual total rainfall of 36.78 inches. The driest year on record was in 1953 with an annual total rainfall of 8.7 inches.

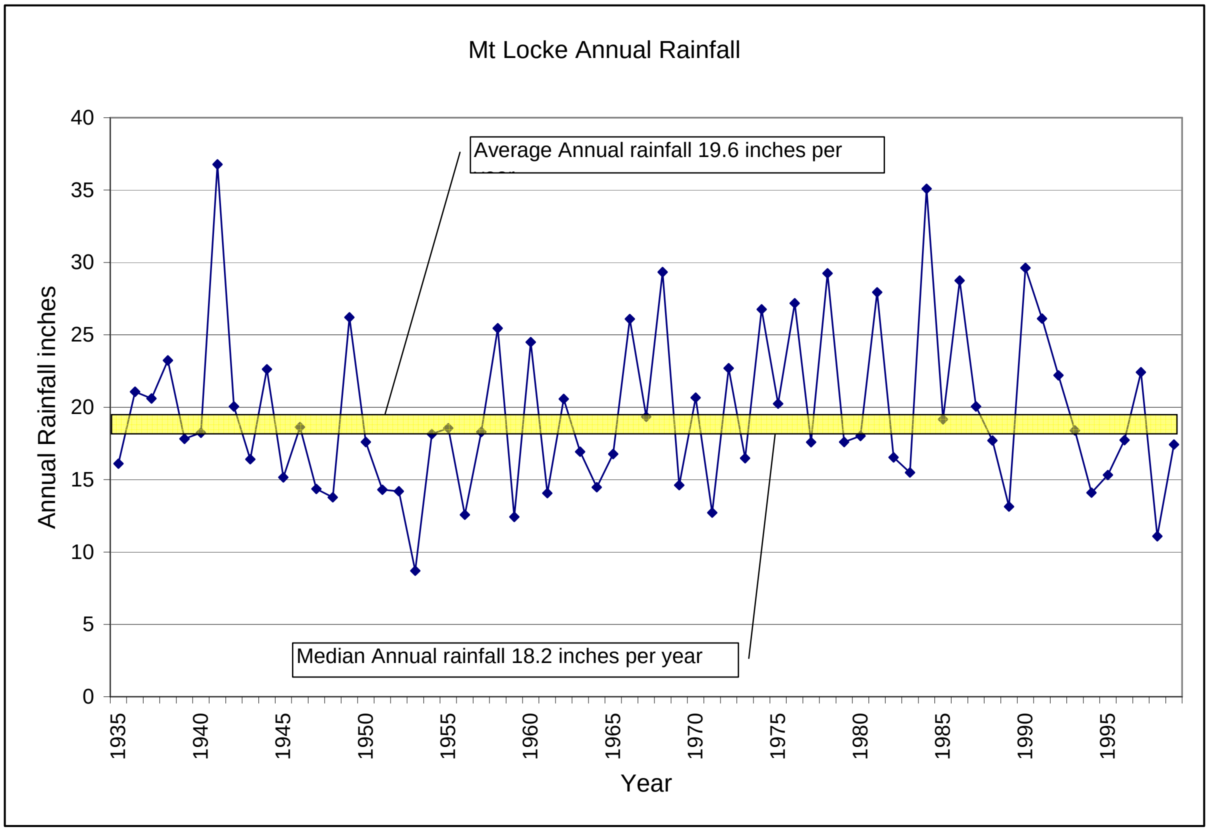


Figure 58. Annual rainfall for Mt. Locke weather station, reported in inches.

The Balmorhea weather station (ID 410498) is located in Reeves County (lat 30.59° N; long 103.44° W) and has historical monthly precipitation totals from 1923 to 1999. The elevation of the weather station is 3,219.3 feet above sea level.

When monthly total rainfall is plotted (Figure 59), the wettest months on record occurred in late summer months: 11.64 inches (September 1932), 11.31 inches (July 1973), 12.11 inches (September 1974), 9.37 inches (September 1978), and 9.57 inches (September 1980). On average, monthly rainfall exceeds two inches in September. The driest month, on average, occurs in March with less than 0.4 inches. Less than one inch of averaged monthly rainfall occurs in January, February, March, April, November, and December. The average monthly rainfall for the Balmorhea station is 1.08 inches per month.

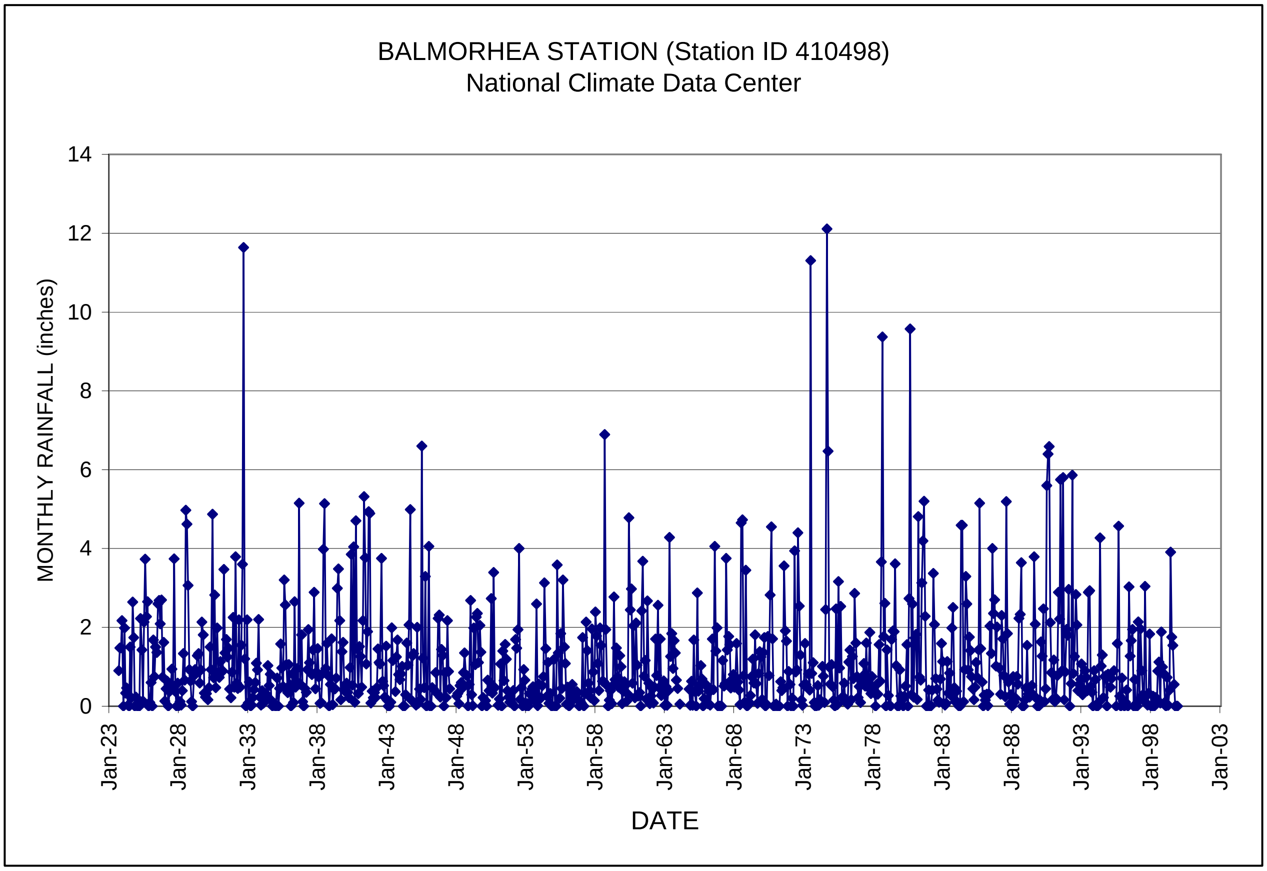


Figure 59. Monthly total rainfall for Balmorhea weather station reported in inches.

When the data is summed annually (Figure 60), the average annual rainfall is 13.1 inches per year with a median value of 12.2 inches per year. The driest period on record occurred from 1993 to 1999, with an average annual rainfall of 9.43 inches per year. The next extended period of below average rainfall occurred from 1950 to 1954. The average annual rainfall during this period was 8.14 inches per year. The wettest year on record was in 1932 with a total rainfall of 28.15 inches. The driest year on record was in 1964 with a total rainfall of 1.13 inches.

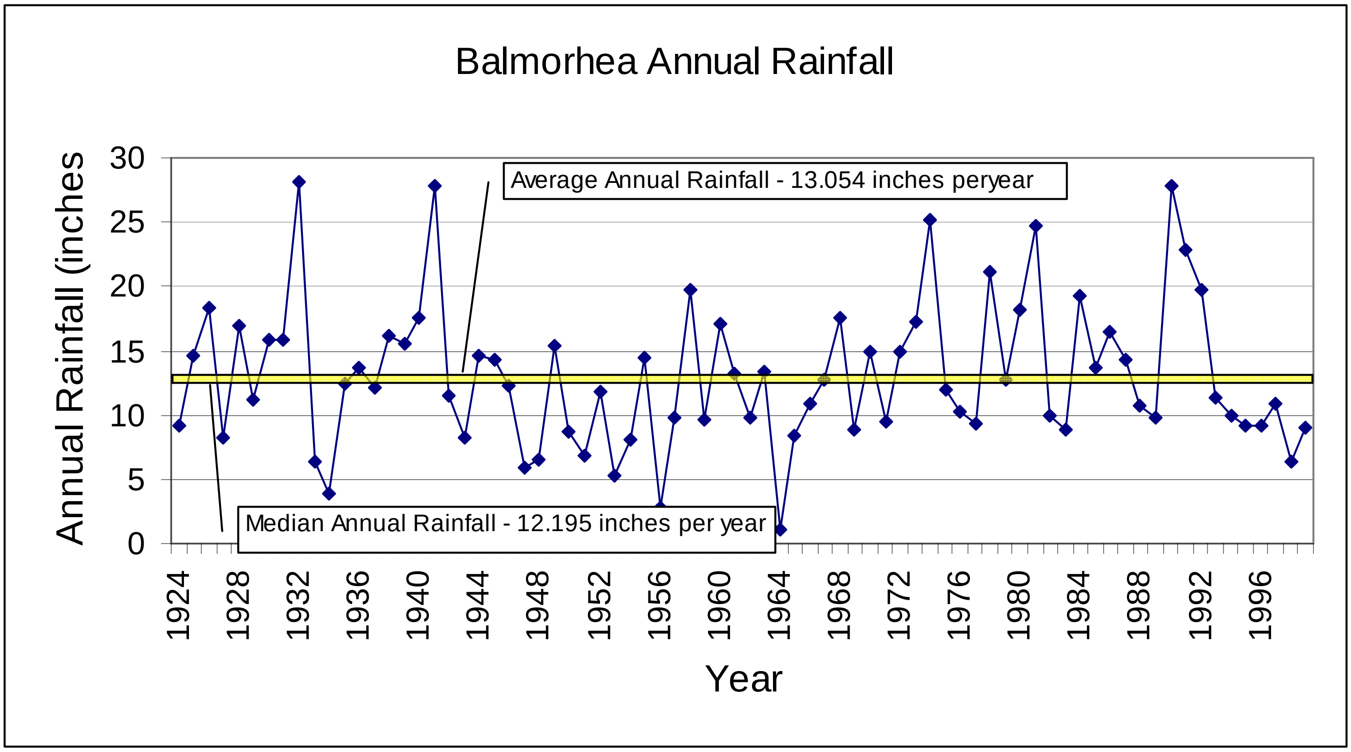


Figure 60. Annual rainfall for Balmorhea weather station reported in inches.

The Van Horn weather station (ID 419295) is located in Culberson County (lat 31.03° N; long -105.50° W) and has historical monthly precipitation totals from 1939 to 1999. The elevation of the weather station is 4,063.9 feet above sea level.

When monthly total rainfall is plotted (Figure 61), the wettest months on record occurred in late summer months: 7.05 inches (September 1941), 9.53 inches (August 1966), 8.59 inches (September 1974), 9.86 inches (September 1978), and 9.02 inches (July 1990). On average, monthly rainfall exceeds one inch in July, August, and September. The driest month, on average, occurs in March with less than 0.18 inches. Less than one inch of averaged monthly rainfall occurs in January, February, March, April, May, June, October, November, and December. The average monthly rainfall for the Van Horn station is 0.83 inches per month.

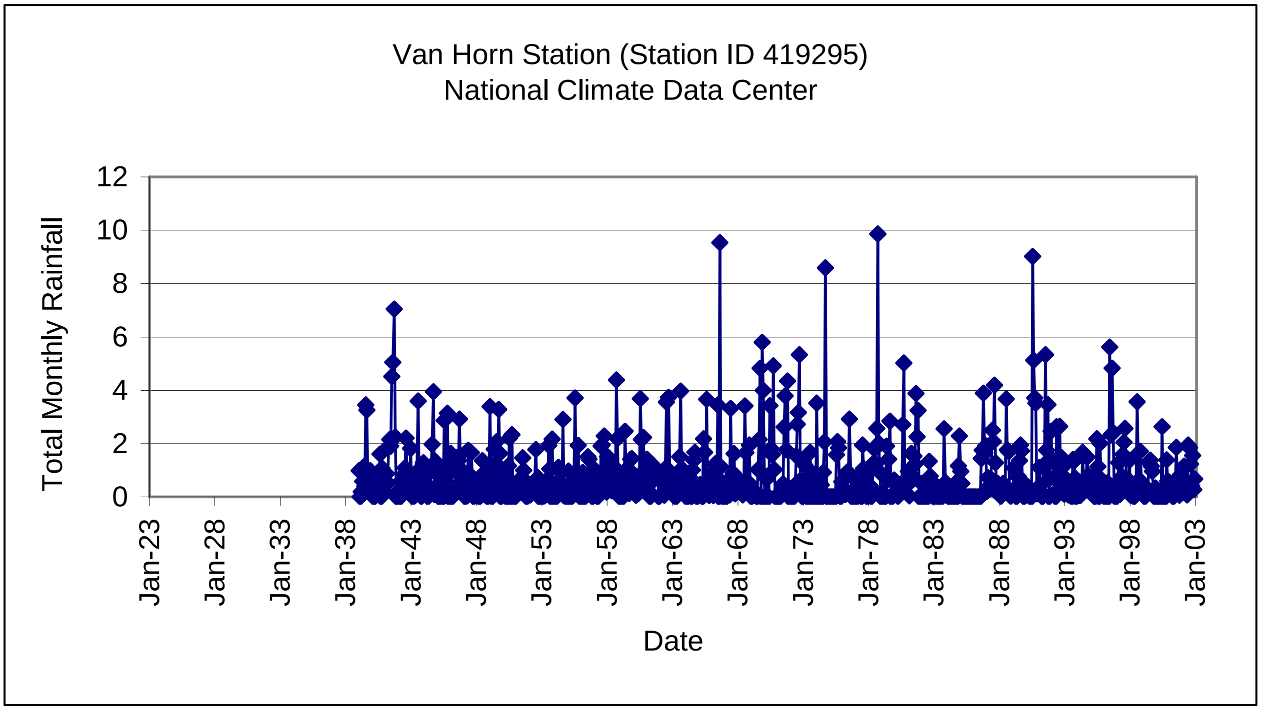


Figure 61. Monthly total rainfall for Van Horn weather station reported in inches.

When the data is summed annually (Figure 62), the average annual rainfall is 9.97 inches per year with a median value of 8.86 inches per year. The driest period on record occurred from 1950 to 1956, with an average annual rainfall of 6.32 inches per year. The next extended period of below average rainfall occurred from 1982 to 1985. The average annual rainfall during this period was 3.31 inches per year. The wettest year on record was in 1941with a total rainfall of 27.27 inches. The driest year on record was in 1985 with a total rainfall of 1.46 inches (this may be due to an incomplete annual record).

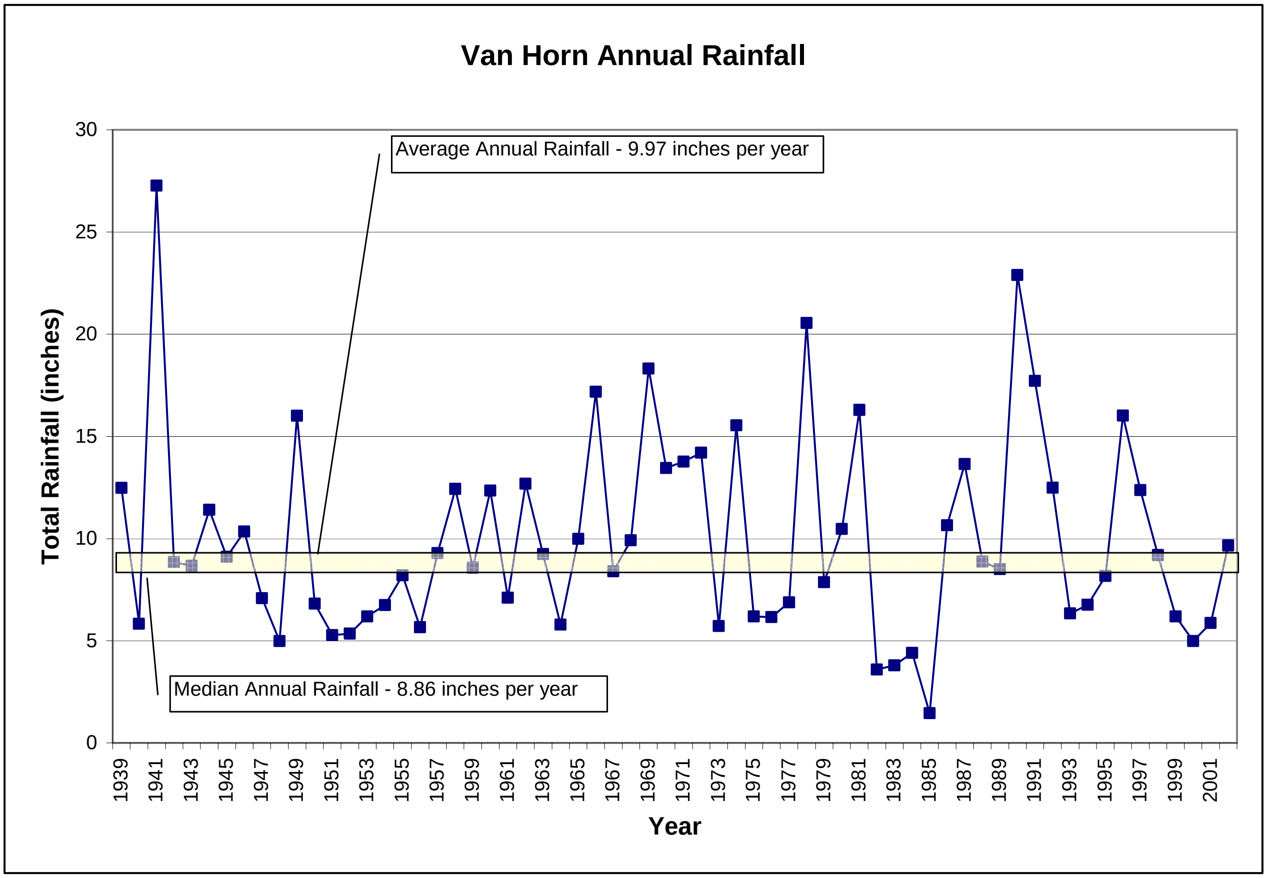


Figure 62. Annual rainfall for Van Horn weather station reported in inches.

3.5.1.2 Rain Gage Measurements

The Timber Mountain rain gage in Jeff Davis County (lat 30°52’24” N; long -103°55’04” W) is located to the south of Phantom Lake Spring (Figure 1). This is on the leeward side of the Davis mountain range. The estimated elevation of the datalogger was set at approximately 3,955 feet above sea level. We collected hourly to quarter-hourly data from April 26, 2001 to June 22, 2003.

When the data is compiled into monthly total rainfall and plotted (Figure 63), the wettest month we recorded occurred September 2001, with 4.68 inches of rainfall. Out of a total of 28 months, we recorded six months that exceeded one inch rainfall: 2.61 inches (July, 2001), 4.68 inches (November, 2001), 1.3 inches (February, 2002), 2.91 inches (July, 2002), 1.22 inches (August, 2002), and 1.8 inches (October, 2002). The driest months were January and April 2003 with 0.01 total rainfall. The average monthly rainfall for this location was 0.88 inches with a median value of 0.66 inches.

In order to analyze for seasonal trends, we applied a two-month moving average trend line. Seasonally, this station experienced a bi-modal distribution pattern with peaks occurring in the summer and fall months. The only full year of rainfall measurements we recorded was 2002, which had a total annual rainfall of 10.12 inches. This suggests the area is still experiencing below-average annual rainfall according to our analysis of the Balmorhea weather station.

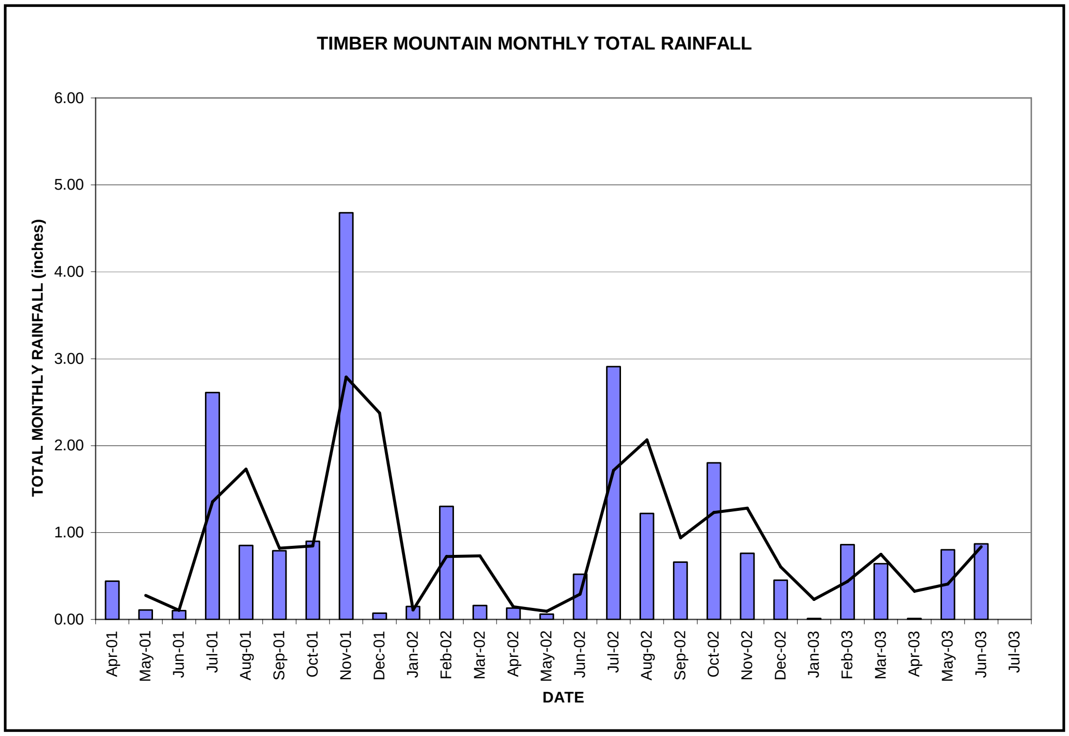


Figure 63. Timber Mountain rain gage summed monthly with a two-month moving average plotted.

The second tipping-bucket datalogger was set up at the Interstate 10 and Interstate 20 intersection (lat 31°05’18” N; long -104°03’34 W). This site is located west-northwest of Phantom Lake Spring near the base of the Apache Mountains close to the Culberson, Reeves, and Jeff Davis county lines on Texas Department of Transportation (TXDOT) property (Figure 1). The estimated elevation of the datalogger was set at approximately 3,996 feet above sea level, slightly higher than the Timber Mountain site. We collected hourly to quarter-hourly data from April 26, 2001, to June 23, 2003.

When the data is compiled into total monthly rainfall and plotted (Figure 64), the wettest month we recorded occurred September 2001, with 5.87 inches of rainfall. Out of a total of 28 months, we recorded eight months that exceeded one inch of rainfall: 2.08 inches (August, 2001), 5.87 inches (November, 2001), 1.29 inches (February, 2002), 1.73 inches (July, 2002), 2.14 inches (October, 2002), 1.04 inches (February, 2003), 2.45 inches (March, 2003), and 1.02 inches (June, 2003). The driest month was January 2001, when the datalogger did not record any precipitation. The average monthly rainfall for this location was 0.93 inches with a median value of 0.63 inches.

In order to analyze for seasonal trends, we applied a two-month moving average trend line. Seasonally, this station experienced a tri-modal distribution pattern with peaks occurring February/March, July/August, and October/November. The only full year of rainfall measurements we recorded was 2002, which had a total annual rainfall of 9.64 inches.

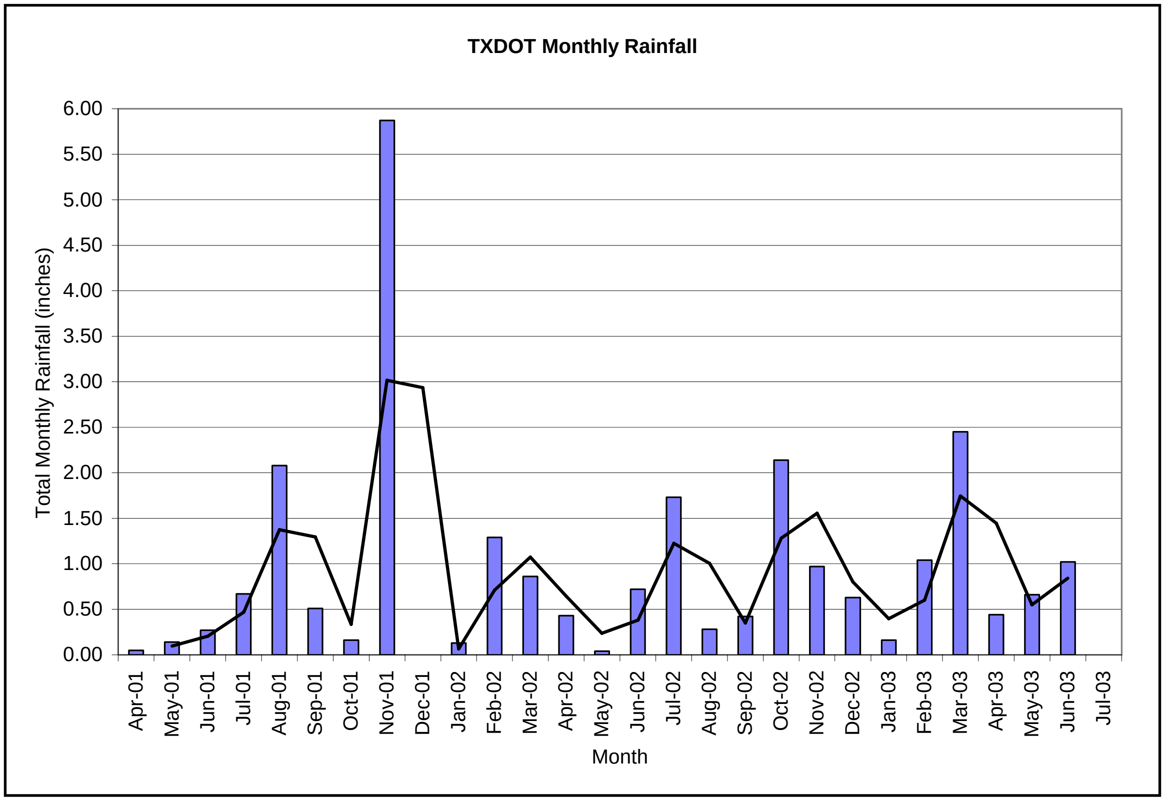


Figure 64. TxDOT rain gage data summed monthly with a two-month moving average plotted.

We then compared total monthly rainfall from the two rain gages and compared the results to the average monthly rainfall from the Balmorhea, Mt. Locke, and Van Horn weather stations (Figure 65). The November 2001, rain appears as an anomaly to regional average conditions. Timber Mountain appears to follow a subdued Mt. Locke average monthly rainfall pattern. The TXDOT gage appears to more closely resemble the Balmorhea average monthly pattern with a two-month delay in peaks.

3.5.2 Pumpage Data Research

We extracted historical groundwater usage for Culberson, Reeves, and Jeff Davis counties from our Water Use Survey database. Initial analysis included totaling usage per category per year for all three counties and plotting the results (Figure 66). Of all the groundwater use in the area, irrigation accounted for 91 percent. Mining accounted for four percent of the total usage, followed by municipal with three percent and livestock with two percent. It is interesting to note that the increase or spike in pumpage that occurred in 1993, occurred during a year of below average rainfall that followed a three-year cycle of above average precipitation.

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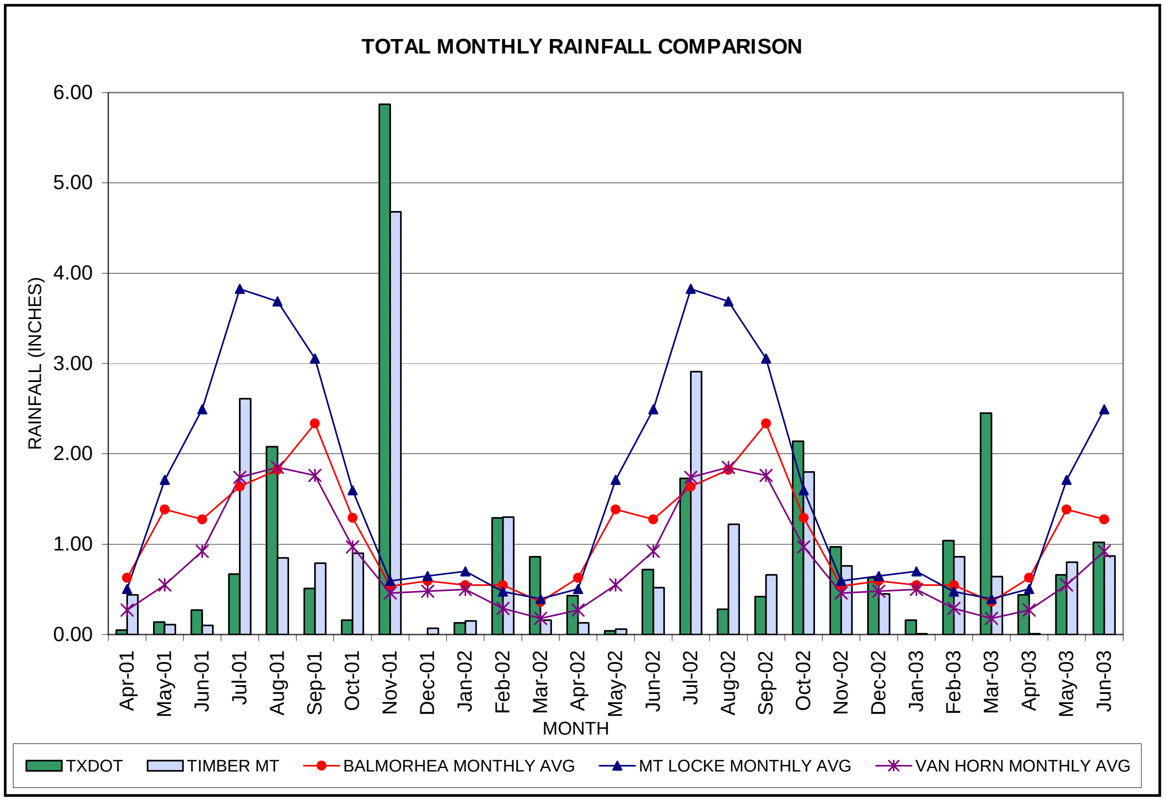


Figure 65. Comparison of rain gage monthly totals to average monthly rainfall for the Balmorhea, Mt. Locke, and Van Horn weather stations.

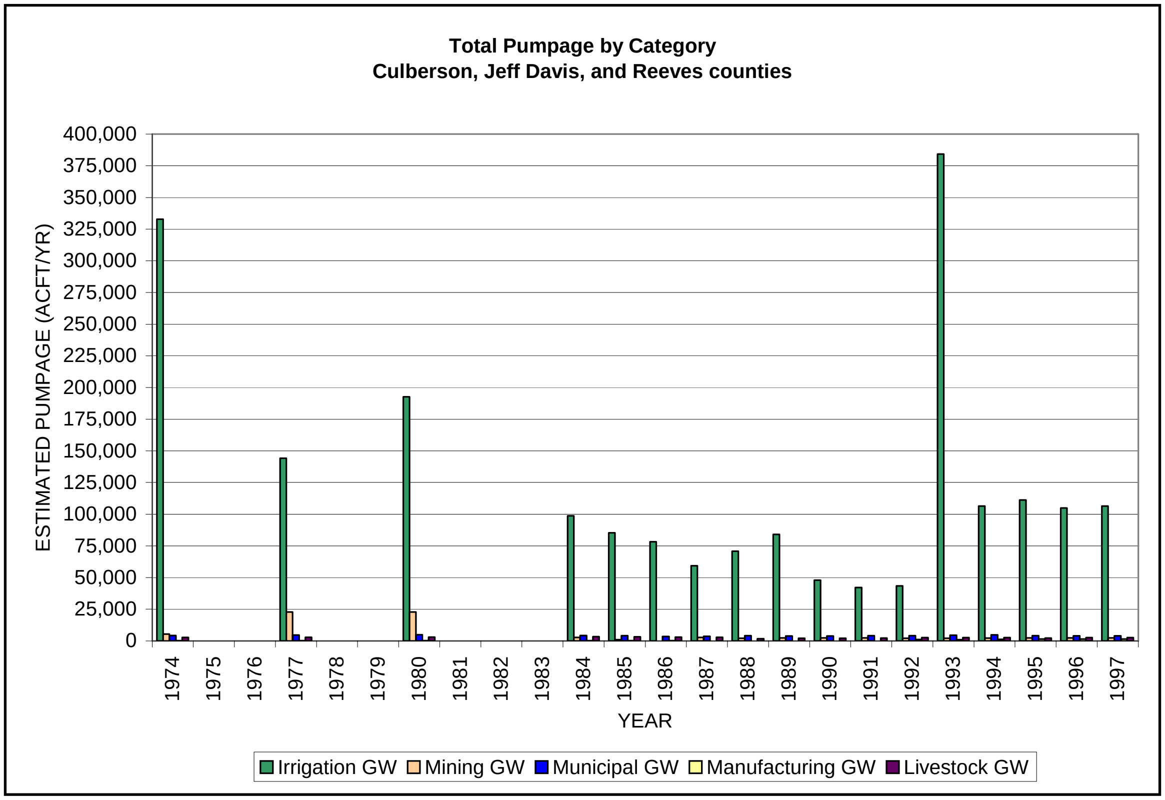


Figure 66. Total pumpage by category summed for Culberson, Jeff Davis, and Reeves counties compiled from TWDB Water Use Survey data.

The next step in our analysis involved extracting groundwater-dependent irrigation data from Report 347 (TWDB, 2001). For state water planning purposes, beginning in 1958 on a five to six year cycle, TWDB staff compiled agricultural use data by major crop and county. We merged total groundwater-dependent irrigation per county with the data in our Water Use Survey database and plotted the results (Figure 67). Reeves County exceeded 150,000 acre-feet of groundwater for irrigation for five years: 1958, 1964, 1969, 1974, and 1993. However, total acreage using groundwater for irrigation in Reeves County has decreased from 414,217 acres in 1964 to less than 75,000 acres in 2000. On the other hand, Culberson County total irrigation peaked in 1979 with a reported 21,105 total acreage using 46, 885 acre-feet of groundwater. In 2000, Culberson County only reported 5,620 acres of farmland using 24,765 acre-feet of groundwater. In the past decade, from 1990 to 2000, Culberson averaged less than 10,000 acre-feet of groundwater and averaged less than 5,000 acres of irrigated farmland.

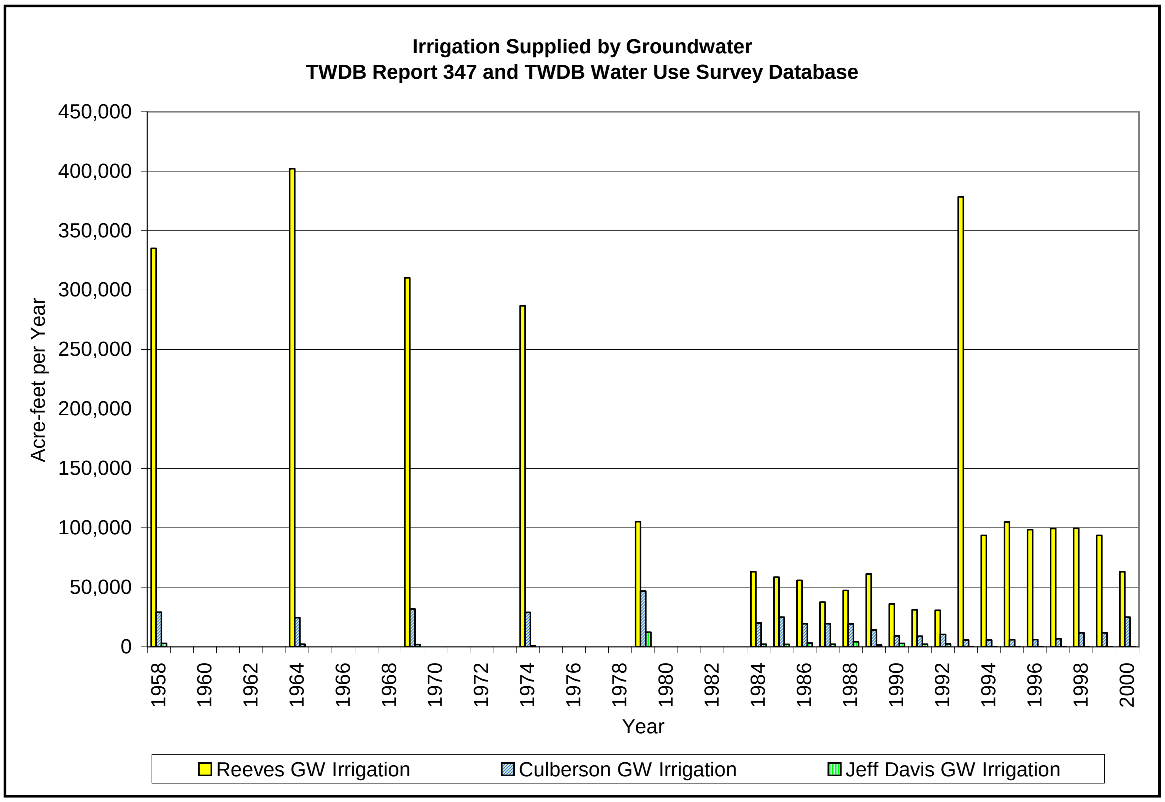


Figure 67. Combination of TWDB Report 347 groundwater irrigation and TWDB Water Use Survey groundwater irrigation reported for the three counties in the study area.

For comparison, we plotted reported usage from selected municipal and mining users (Figure 68). The Duval/Freeport McMoran Sulfur Mine in Culberson County began production in 1967 and ceased operations in 1999 with groundwater usage exceeding 4,000 acre-feet from 1967 through 1980. The remaining municipal user's average annual use is significantly less: City of Pecos averaged 1,118 acre-feet per year, City of Van Horn averaged 546 acre-feet per year, Madera Valley McIntyre well field averaged 185 acre-feet per year, Madera Valley Huelster well field averaged 140 acre-feet per year, and City of Balmorhea averaged 120 acre-feet per year.

3.5.3 Spring Discharge

San Solomon, Phantom Lake, and Giffin Springs USGS discharge records were compiled and plotted for comparison (Figure 69). We located discharge records from 1965 to 2001for San Solomon Springs. San Solomon Springs is the largest of the three springs with an average discharge rate of 29.96 cubic feet per second. A maximum discharge value of 83.2 cubic feet per second occurred on October 31, 1975. The minimum discharge value on record occurred the previous year on January 8, 1974 (17.6 cubic feet per second). The linear trend line for San Solomon, *y=-0.0001x+33.042,* suggests a slight decline in discharge over time. The peaks in discharge suggest an influence from influxes in the flow system possibly related to rain events. The majority of the peaks correspond to those recorded at Phantom Lake Spring. The USGS records indicate a gap in discharge measurements from October 22, 1975, to December 3, 1975. This may explain why Phantom Lake Spring does not show a corresponding peak for the October 1975 event.

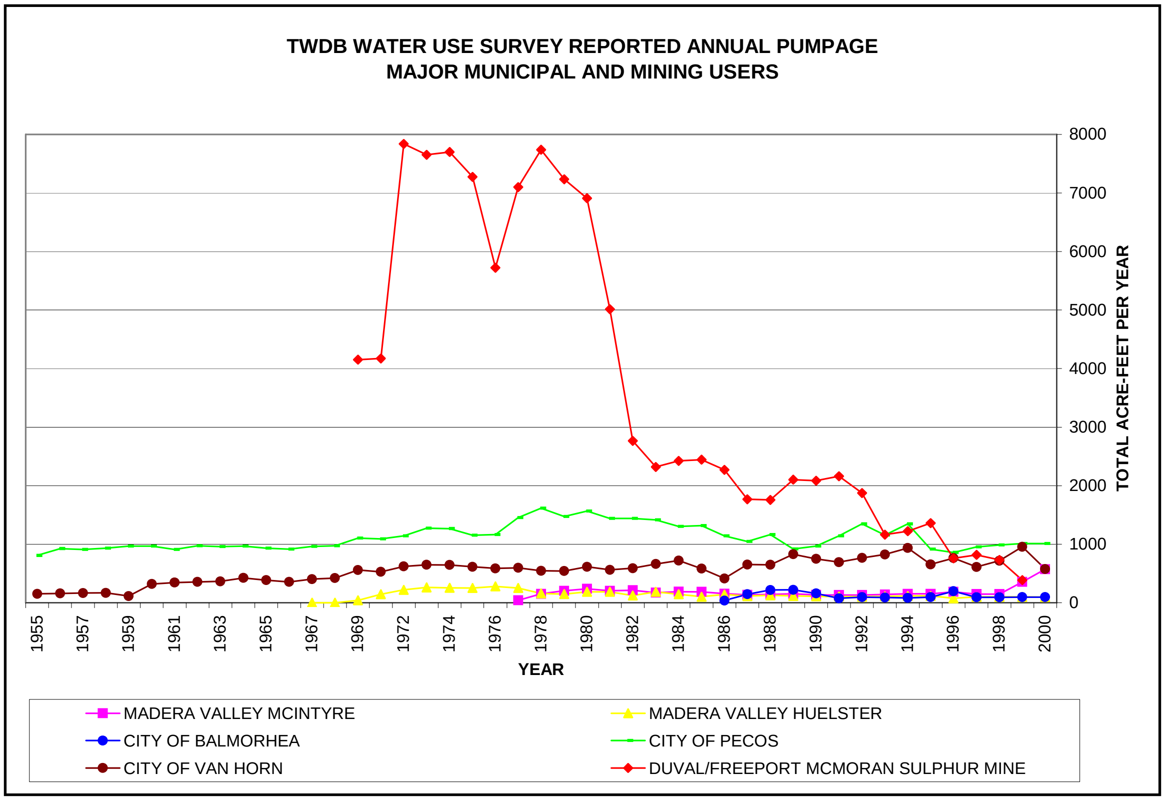


Figure 68. Combination of TWDB Report 347 groundwater irrigation and water use survey groundwater irrigation reported per county.

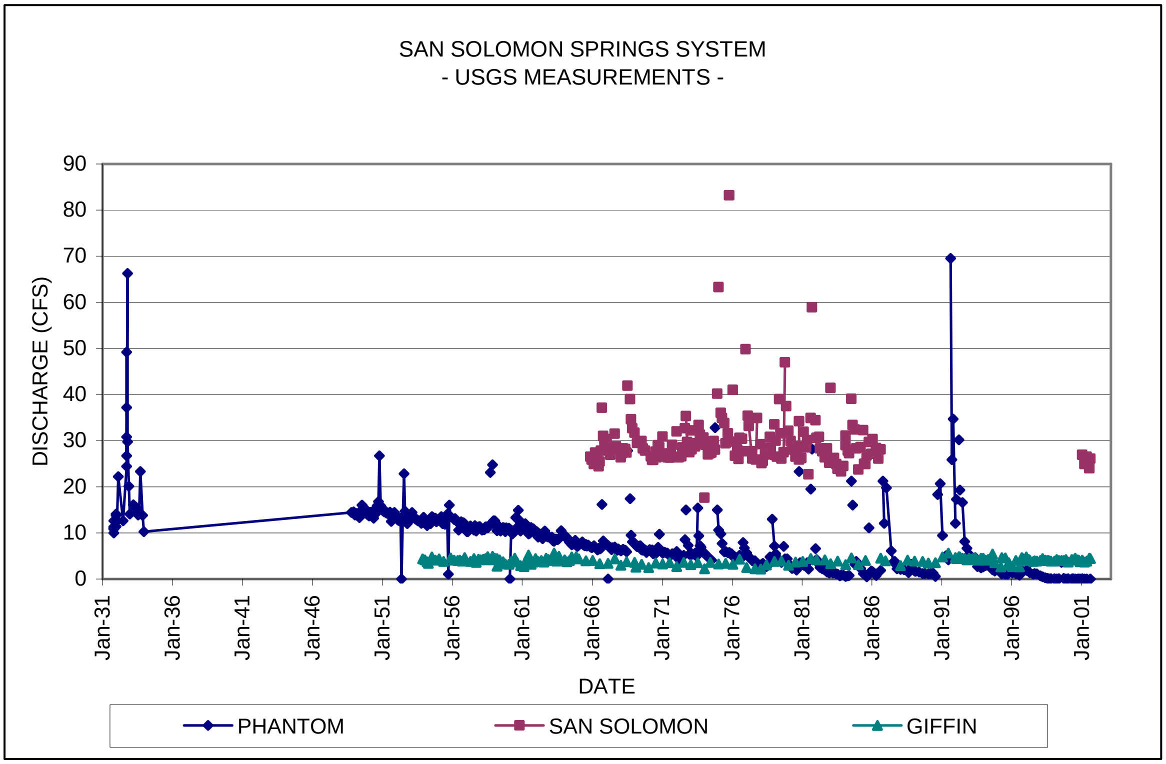


Figure 69. Phantom Lake Spring, San Solomon Springs, and Giffin springs historical discharge measurements (USGS).

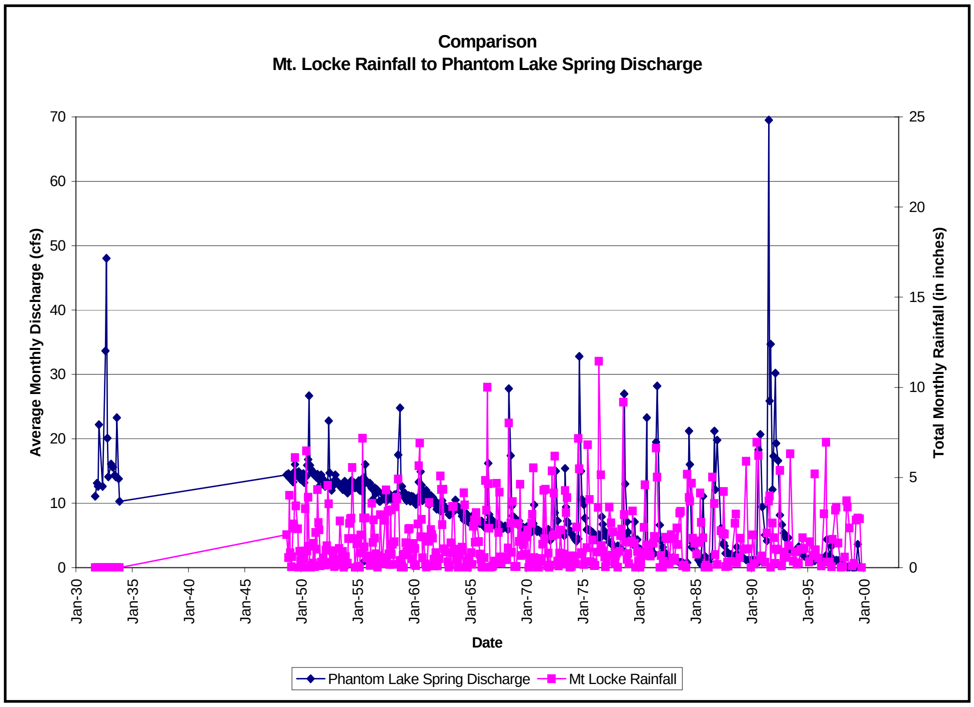
The USGS data indicates that Phantom Lake Spring was the second largest spring until the late 1970s. Between October 16, 1931 and August 28, 2001, the average discharge rate was 8.93 cubic feet per second, with a linear trend line of $y=-0.0006x+25.037$. The average discharge rate slowed to 4.72 cubic feet per second between 1983 and 2001. Since 1994, discharge rates have averaged less than one cubic feet per second. Phantom Lake Spring exhibits periodic peaks in discharge that roughly correlates to localized rain events. The discharge exceeded 60 cubic feet per second on August 15, 1991 (69.5 cubic feet per second) and October 5, 1932 (66.3 cubic feet per second).

We compiled discharge records for Giffin Springs from between 1953 to 2001. Giffin Springs has been the most consistent over time with an average discharge rate of 3.94 cubic feet per second. The maximum value recorded for discharge was 5.65 cubic feet per second on June 26, 1991. The minimum value recorded for discharge was 2.14 cubic feet per second, January 10, 1978.

3.5.4 Comparison: Rainfall, Discharge, and Pumpage

To correlate peaks in discharge with localized rainfall, we plotted average monthly USGS discharge measurements for Phantom Lake Spring and included the Mt. Locke and Balmorhea weather stations total monthly rainfall for comparison (Figure 70). Discharge peaks correspond to rainfall events and normally appear when monthly rainfall is in excess of around four inches, preferentially in September. In contrast, not all wet months are mirrored with an elevated discharge at Phantom Lake Spring, nor is there a correlation to monthly rainfall amount and intensity or duration of flow spikes at the spring, especially in more recent years. Further research would be needed to investigate antecedent soil conditions and weather patterns with discharge at the springs to determine if a correlation with finer resolution exists.

Since irrigation is by far the largest consumer of groundwater in the region, we plotted annual reported groundwater use with annual rainfall to investigate the relationship between farming, rainfall, and consumptive groundwater use (Figure 71). Increased groundwater usage for irrigation roughly corresponds to years with below average rainfall. For example in Reeves County 1964, 1969, 1989, and 1993 were relatively dry years with high groundwater use. Additional research indicates a substantial increase in acreage for alfalfa in Reeves County contributed to the spike observed in figure 71 in 1993. According to the Van Horn weather station annual rainfall measurements, 1964, 1979, 1985, and 2000 were relatively dry years in Culberson County. Reported groundwater use increased during these same years. However, it should be noted that in years of high rainfall, groundwater use did not necessarily drop. Generally, increased groundwater use for irrigation may be associated with the establishment of a new perennial crop and/or plant need due to insufficient rainfall during key periods of the growth cycle. Therefore, the timing, intensity, and duration of rain during the growing season are important factors to consider. Comparisons of groundwater use to annual rainfall may not be of a sufficient scale to reflect this.



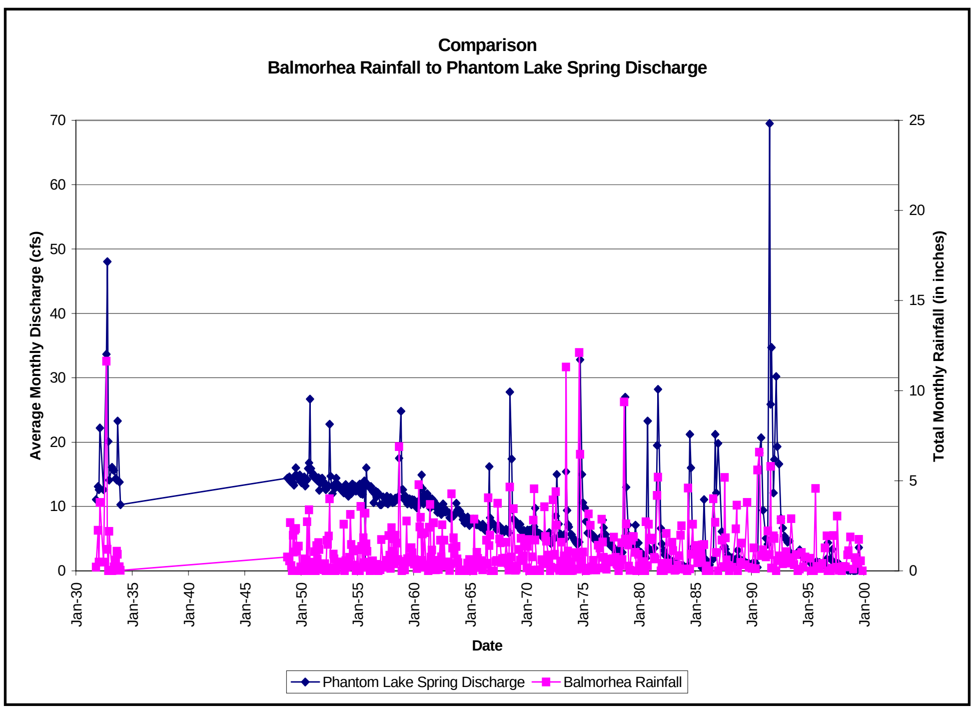
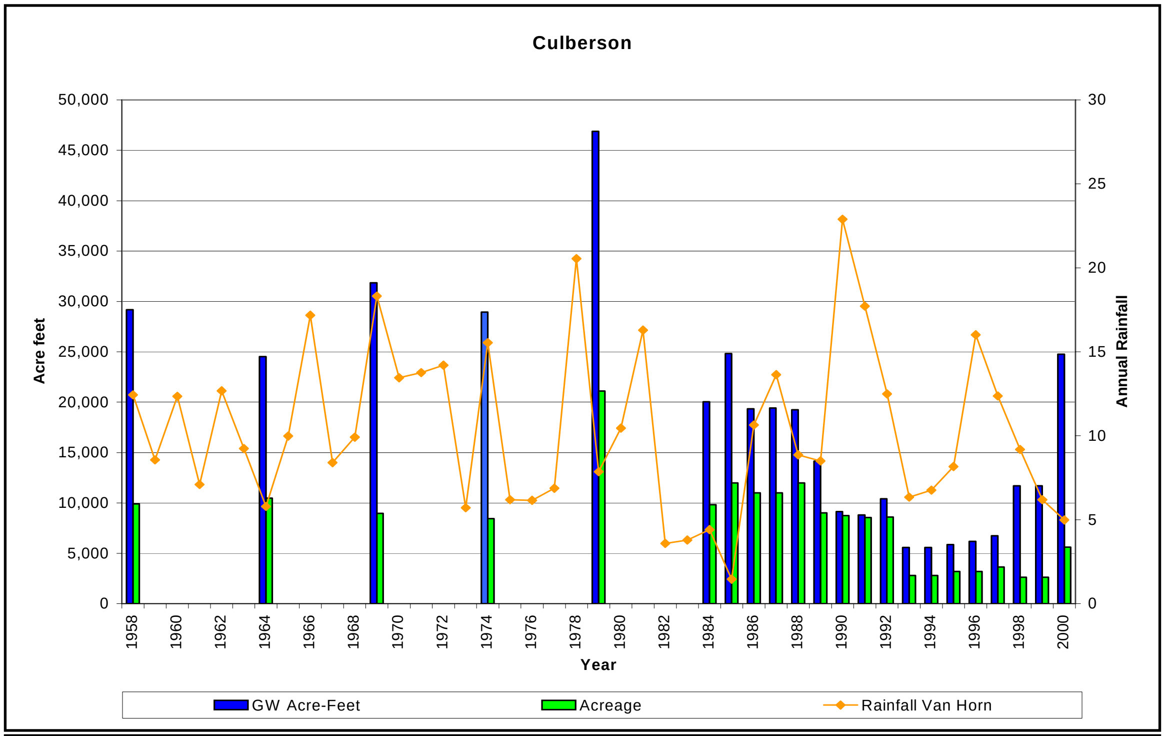


Figure 70. Comparison of discharge at Phantom Lake Spring and monthly rainfall recorded at the Mt. Locke (top graph) and Balmorhea (bottom graph) weather stations. Note: Mt. Locke did not start recording rainfall until 1935.



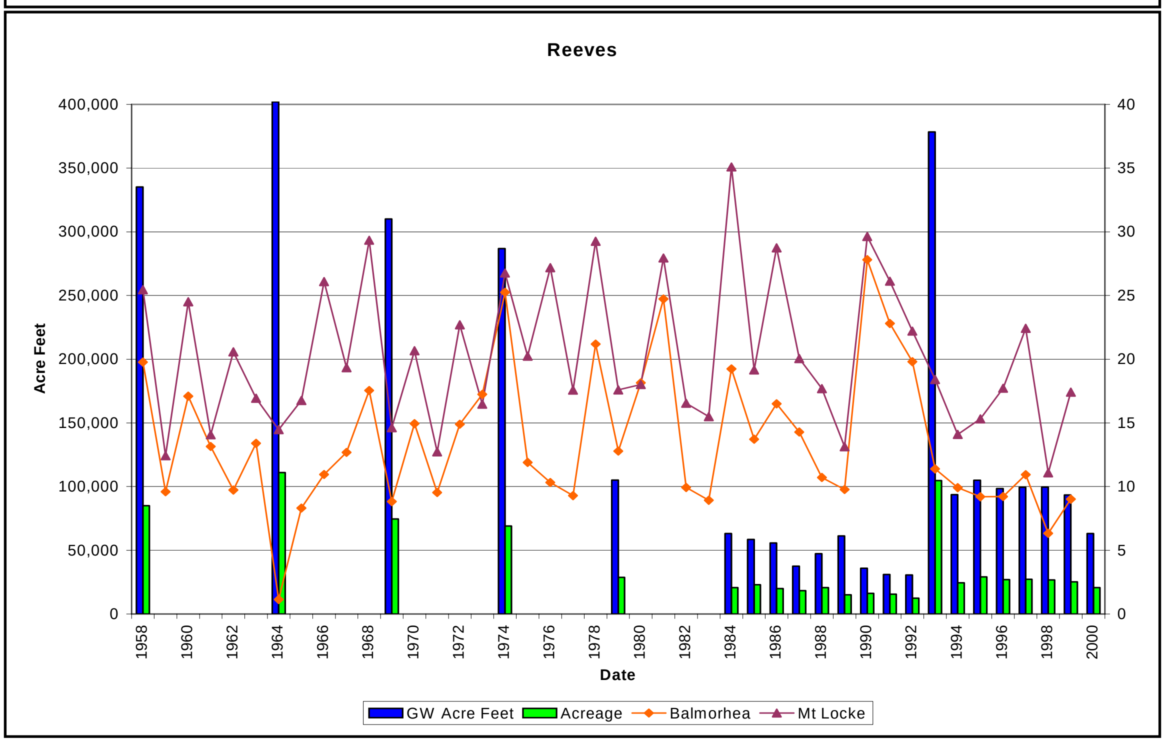


Figure 71. Comparison of historical irrigation pumpage and annual rainfall. Top graph compares Culberson groundwater acreage for irrigation, groundwater usage for irrigation, and annual rainfall from the Van Horn weather station. The bottom graph compares Reeves groundwater acreage for irrigation, groundwater usage for irrigation, and annual rainfall from Balmorhea and Mt. Locke weather stations.

Since Culberson County contains the proposed source waters than maintain base flow at Phantom Lake Spring, we plotted annual irrigation supplied by groundwater, annual rainfall measured at the Van Horn weather station, and average annual discharge at Phantom Lake Spring (Figure 72).

In 1958, Phantom Lake Spring had an average discharge of 13.4 cubic feet per second, rainfall totaled 12.43 inches, and irrigation consumed 29,176 acre-feet per year of groundwater. In contrast, in 1974, irrigation used 28, 935 acre-feet of groundwater, rainfall was higher at 15.54 inches, yet discharge at Phantom Lake Spring fell to an annual average discharge rate of 8.98 cubic feet per second. Five years later (1979), the highest documented consumption of groundwater was recorded at 46,885 acre-feet per year when annual rainfall dropped to 7.86 inches, and discharge at Phantom Lake Spring fell to an average annual rate of 4.95 cubic feet per second.

Average annual discharge at Phantom Lake Spring rose to a high in 1991 (22.98 cubic feet per second), which was the highest average discharge recorded from 1958 to 2000. The lowest recorded average annual discharge at Phantom Lake Spring occurred in 2000 (0.03 cubic feet per second). The highest annual rainfall for the same period occurred in 1990 (22.89 inches) and the lowest annual rainfall was recorded in 1985 (1.46 inches). Again the highest use of groundwater occurred in 1979 (46, 885 acre-feet per year) and the lowest was reported in 1994 (5,583 acre-feet per year).

Between 1993 and 2000, the average discharge at Phantom Lake Spring was one cubic feet per second, the average rainfall was nine inches, and irrigation averaged 9,771 acre-feet per year. Comparatively from 1983 to 1990, the average discharge at Phantom Lake Spring was four cubic feet per second, rainfall still averaged nine inches per year, and pumpage averaged 18,027 acre-feet per year.

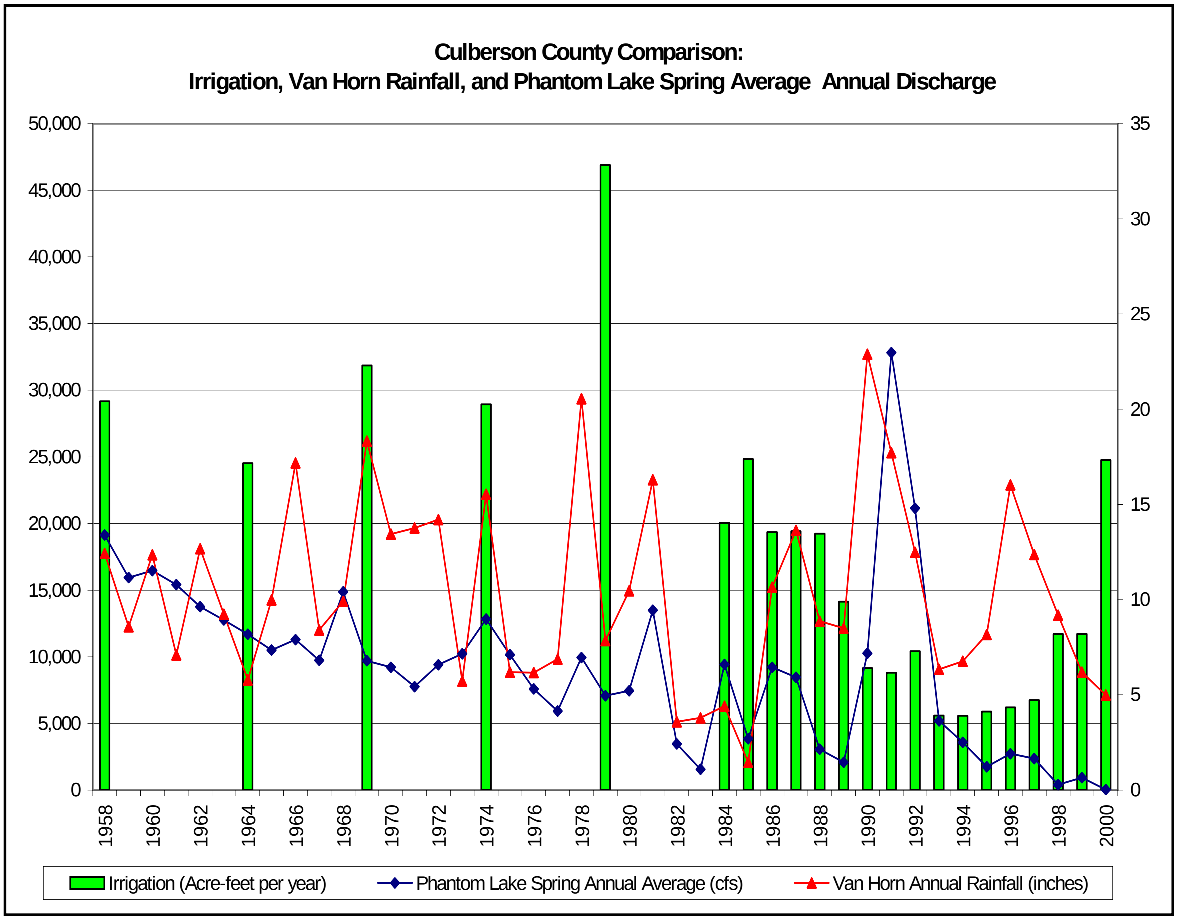


Figure 72. Comparison of annual groundwater use for irrigation in Culberson County (acre-feet per year), total annual rainfall from Van Horn weather station (in inches), and average annual discharge at Phantom lake Spring (cubic feet per second).

4.0 DISCUSSION OF FINDINGS

The primary objectives of the study were to study the hydrogeology of source aquifers for the San Solomon Springs system and to evaluate the effect, if any, of groundwater well usage on spring flow. The following subsections outline the objectives listed in the original proposal and the results of our investigation.

4.1 Delineation of the recharge and discharge areas of springs

Based on the water quality information, two different source areas of groundwater exist for Phantom Lake, San Solomon, Giffin, and East Sandia springs: Delaware and Apache Mountains to the west and the Davis Mountains to the south. We observed that the sodium to chloride (Na/Cl) ratios of the Phantom Lake, San Solomon and East Sandia springs are nearly identical: 0.63, 0.63, and 0.70, respectively (Figures 34 and 39). Sulfate to chloride (SO_4/Cl) ratios are also considerably lower in the Phantom Lake, San Solomon and East Sandia springs (0.69, 1.09, and 1.08, respectively) than the rest of the samples. This compositional trend is in sharp contrast to the fresh waters derived from wells sampled (3, 4, 9, and 10) down-dip from the Davis Mountains (Figures 33 and Table 6). The sodium to chloride (Na/Cl) and sulfate to chloride (SO_4/Cl) ratios clearly indicate that the spring waters derived most of the minerals from dissolution of halite and gypsum. In the shallow subsurface between the springs and the Davis Mountains no gypsum or halite deposits occur (White and others, 1941) which precludes the Davis Mountains to be a dominant source area for the spring waters under any regular steady-state conditions.

Isotopic information from the springs and the groundwater wells from the Apache Mountains and west of the Delaware Mountains indicate these areas to be the source of the springs. The Oxygen-18 ($\delta^{18}O$) and Deuterium (δ^2H) values of the groundwater samples from the Davis Mountains wells are more enriched indicative of modern to sub-modern groundwater while the rest of the samples west of the springs and west of the Delaware Mountains indicate that recharge occurred under a humid climate during late Pleistocene period (Figure 40). Tritium and Carbon-14 data support a similar conclusion drawn from the water quality results. The isotope data suggest that the waters from the Davis Mountains wells are relatively young but the rest of the samples are 10,000 to 18,000 years old before present. Sulfur-34 data suggest that the spring waters were derived from dissolution of gypsum as much of the sulfate bore characteristic isotopic signatures of the Permian evaporite that occurs west and northwest of the Salt Basin.

From our detailed investigation, we conclude that the elemental and isotopic compositions between the springs, Apache Mountains' area, and areas west of the Delaware Mountains are similar. We observe from the literature that several north-south faults occur in the area (Nielsen and Sharp, 1985; Uliana, 2000) that could potentially act as flow conduits (Figure 47). These waters also lie at an elevation higher than the elevation at the springs. Geochemical modeling supports that the final water composition in the springs can be achieved if groundwater from west of the Delaware Mountains flowed southeast through the extensively faulted Permian and the Cretaceous sediments. Water-level data also indicate that the area is only weakly disconnected hydraulically from areas further south in the Salt Basin and perhaps this may not translate to the occurrence of groundwater divides in the deeper units below the Salt Bolson. In addition, we also observe that wells completed in the Salt Bolson and Delaware Mountain Group have similar elemental composition (Table 7). Thus, wells in the Delaware Mountains could potentially have similar chemical and isotopic signatures as those of the springs and wells sampled west of it. Should this be the case, groundwater from the Delaware Mountains could also be guided by faults to discharge near its southern flanks where it meets groundwater from the west of Apache Mountains. One perhaps also cannot rule out the fact that smaller amounts of deeper saline water may have flowed upward into the aquifers of the Delaware Mountain Group and the Capitan Reef aquifers through faults and mixed with the fresher water contained in the host aquifers.

Based on the above lines of evidence, we suggest that groundwater from the Delaware Mountains and areas west of it follows the fault zones in the south and mixes with the waters from the Apache Mountains to reach the springs under a steady-state base flow condition. During intense local rainfall events, which are rather rare on a historic scale, changes occur to the traditional supply source when the spring waters receive much of the flow from the Davis Mountains for a relatively short period.

White and others (1941) first documented the Davis Mountains as a source of water to the springs during flash floods and heavy, local rainfall. Figure 70 correlates peak discharge at Phantom Lake Spring with historical periods of heavy rainfall at both the Balmorhea and Mt. Locke weather stations. On average, higher amounts of precipitation occurs at higher elevations. Rainfall either directly enters the groundwater flow system through sinks and fractures or through segments of losing streams. The stream gain-loss study by White and others (1941) indicates a recharge zone exists in an area approximately three miles wide about three miles south of the Jeff Davis-Reeves county line in a zone that parallels the county line. Mountain run-off that accumulates in the streambeds of Madera, Little Aguja, Aguja, and Cherry creeks crosses over this area and then recharges the aquifer that feeds the springs. On a smaller scale, rainfall in the immediate area surrounding the springs directly enters the system through local sinks and fractures in the areas where limestone is exposed at the surface and in areas where the Cenozoic Pecos Alluvium is exposed rainfall percolates through gravels and terrace materials to enter the flow system.

Discharge of the groundwater flow system in the Balmorhea area generally occurs at the contact of the Buda Limestone and the underlying Boracho Formation (Figure 49). In areas where the Cenozoic Pecos Alluvium covers the Cretaceous rocks, groundwater either percolates up through alluvium and forms pools, such as the artesian springs of San Solomon and Giffin, or collects in the more porous alluvium and flows down gradient in a northeasterly direction, such as the gravity fed East Sandia Springs.

4.2 Delineation of groundwater flow paths

As discussed above, we conclude there are at least two source areas to the San Solomon Springs system; one derived from the south in the Davis Mountains and the other from the from the Apache Mountains and Delaware Mountains area. While we support the contention expressed by earlier researchers (Nielson and Sharp, 1985) about the existence of groundwater divides in the Salt Basin, we believe that the divides may not be strongly developed, and they may not readily apply to the deeper geological units below the Salt Bolsons. Numerous northwest to southeast and east to west trending fault zones occur between the northwestern portion of the Diablo Plateau and the Delaware Mountain Group across the salt flats (Figure 47). These fault zones can potentially act as flow conduits for the groundwater and could lend some support for groundwater flow to occur from beyond the Wild Horse Flats area to the springs (Figures 22 and 23).

In a recent investigation, Lee and Williams (2000) reconstructed the paleohydrology of the Delaware Basin indicating that meteoric water that recharged from the uplifted western margin discharged basin ward. Hydrocarbons migrated by pressure gradients and buoyancy and discharged upwards along faults into the western basin. Thus, saline water from the deeper subsurface can move upwards into the overlying Delaware Mountain Group and the Capitan Reef aquifers.

During high precipitation events in the Davis Mountains, there is a groundwater flow component from the south to southwest that flows north to northeast to the springs. In addition, a regional base flow component originates at least as far as the northwest corner of Culberson County from the Delaware Mountains area. The water from this source flows south to southeast to the Apache Mountains, then flows in a more easterly direction along the Stocks fault and discharges at the springs. Currently San Solomon, Giffin, and East Sandia appear to be relatively stable as reflected in their near constant discharge (Figures 15, 16, 17, and 69). Because Phantom Lake Spring is the first discharge point of the spring system (Figures 1, 20, 21, 22, 23, and 49) and is at a higher elevation than the remaining springs (Figure 49), reductions in head may understandably be initially reflected in the lowering of water-levels at Phantom Lake Spring (Figures 13 and 69).

4.3 Estimation of local versus regional recharge to the springs and aquifers

NETPATH geochemical modeling indicates that a substantial amount (up to 55 percent) of the total groundwater in the springs can potentially be derived from the Apache Mountains and west of the Delaware Mountains (Table 11). NETPATH derived travel time indicate that the groundwater from the west and the northwest could flow at a rate of 0.8 to 0.9 feet per day through the fault zone towards the springs. If our estimation of the flow rate is correct, then it is plausible that most of the groundwater near the springs probably accumulated long ago.

The area has experienced below average rainfall in more recent years (Figures 63, 64, and 65) and a significant local recharge event was not observed in spring flow during the duration of this study. Using NETPATH and data collected during 1932 when considerable increases in spring discharge were observed after heavy rain events causing flash floods, we estimate up to 95 percent of the flow at Phantom Lake Spring was derived from the Davis Mountains and 5 percent was derived from the Apache Mountains direction (Table 14). This example represents the high-end range of local contribution since traditionally heavy rainfall events rarely occur and are not as extreme in intensity or as long in duration.

4.4 Determination of hydraulic properties of the aquifers

Wells completed either fully or partially in the Delaware Mountain Group have average transmissivity values of 1,540 feet squared per day (Table 17). The average transmissivity value for wells completed entirely or partially in the Capitan Reef complex is around 20,000 feet squared per day. Comparatively, wells completed solely in the Salt Bolson have average transmissivity values of 3,400 feet squared per day while wells completed solely in the Cretaceous Formation averaged 1,500 feet squared per day. It should be noted that in areas where fractures are dissolved, transmissivity or flow may exceed average conditions, since the fractures may plausibly act as major conduits for groundwater flow.

4.5 Description of the interaction between surface water and groundwater

There are no perennial streams in the study area. As discussed above in section 4.1, runoff infiltrates or directly recharges the groundwater flow system through faults and sinks or in losing portions of streams (White and others, 1941; Couch, 1978; and LaFave and Sharp, 1987). Recharge is achieved in losing portions of streams only when rainfall is of a sizable intensity or duration for runoff to accumulate in the streams and maintain a sufficient flow to reach the recharge zone. Direct recharge or infiltration also occurs in the immediate area surrounding the springs through fractures, sinks, and porous materials, such as gravels, located at the surface.

4.6 Calculation of water balances

The combined flow from Phantom Lake and San Solomon Springs averages around 33,000 acre-feet per year (LaFave and Sharp, 1987). Previous studies and modeling by Nielson and Sharp (1985) suggest 2, 850 acre-feet per year could be contributed from the southern portion of the Salt Basin. The results of the NETPATH model runs suggest up to 55 percent of the flow at the springs could be derived from from the Apache Mountains and west of the Delaware Mountains. This equates to around 18,150 acre-feet per year. Additional water is supplied from local recharge both around the discharge area and from the Davis Mountains. However, as discussed previously, rainfall must be of a sizable intensity or duration to contribute to the flow system. A storm of this magnitude was not observed in the measurements taken at the springs during the monitoring phase of this study.

4.7 Evaluation of impacts on springs from regional groundwater pumping

Information on pumpage dating from the 1940s is not available for a direct comparison of pumpage to the diminishing spring flows observed at Phantom Lake Spring (Figure 72). The pumpage data we obtained (1958 to 2000) indicates the heaviest groundwater use occurred in the region from the late 1950s through 1980, with the exception of reported irrigation in Reeves County in 1993 (Figure 71). One would normally expect water levels to rebound after groundwater use declines and periodic episodes of heavy rainfall occur. Phantom Lake Spring does exhibit surges of elevated discharge, however this is short-lived and appears directly associated with local recharge from the Davis Mountains as opposed to responses to reduction in pumpage (Figures 71 and 72). However, as suggested in Section 4.1 above, if most of the base flow to the springs consists of ancient groundwater that accumulated long ago, any extraction of this water from the system anywhere along the flow path may adversely affect water levels. Another possibility is that reductions in pumpage in Culberson County may not immediately be reflected at the springs due to the regional scale and travel time. Therefore, it appears that even with reductions in pumpage over time, insufficient recharge to the source waters has occurred to balance the system.

We used the annual TWDB Water Use Survey for reported pumpage from selected entities (Figure 68). The major local municipal users that utilize groundwater in and around the discharge area of the springs include Madera Valley Water Supply Corporation (McIntyre and Huelster well fields) and the City of Balmorhea. Of these, only the Madera Valley McIntyre well field is directly on the hypothesized flow path of the base flow that originates in and beyond the Apache Mountains area. Figure 68 also shows the pumpage associated with the Duval/Freeport McMoran Sulfur mining operation that withdrew large quantities of groundwater in conjunction with their mining process during the 1970s around the Reeves/Culberson county line. They have since ceased operations. When estimates for irrigation groundwater withdrawal is plotted and compared against summed municipal, mining, manufacturing, and livestock categories for these counties (Figure 65), the pumpage plotted by the selected entities in Figure 68 appears insignificant.

Irrigation accounts for the majority of groundwater use in Reeves, Culberson, and Jeff Davis counties (Figure 65). Generally, increased groundwater use for irrigation may be associated with the establishment of a new perennial crop and/or plant need due to insufficient rainfall during key periods of the growth cycle. Increased groundwater usage for irrigation appears to roughly correspond to years with below average rainfall, for example 1964, 1969, 1989, and 1993 in Reeves County and 1979, 1985, and 2000 in Culberson County (Figure 71, top). While 1993 was a relatively dry year following three wet years for Reeves County, additional research indicates a substantial increase in acreage for alfalfa in Reeves County contributed to the spike observed in Figure 71(bottom).

Since Culberson County contains one of the source areas for the springs and irrigation is the highest category of use, we concentrated our efforts in researching trends in irrigation in this area. Overall, groundwater pumpage has decreased in Culberson County in the past twenty years. Groundwater use for irrigation peaked in 1979 with a reported 21,105 total acreage using 46, 885 acre-feet of groundwater (Figure 71, top). In 2000, Culberson County only reported 5,620 acres of farmland using 24,765 acre-feet of groundwater. In the past decade, from 1990 to 2000, Culberson County averaged less than 10,000 acre-feet per year of groundwater for agricultural use and averaged less than 5,000 acres of irrigated farmland.

While pumpage along the flow path from the source waters to the springs, may well affect base flow at the springs, diminishing flows at Phantom Lake Spring were already occurring before many wells were drilled and heavy groundwater use was reported (Figures 69 and 72). We recommend additional research to explore other components that may cause or contribute to the conditions observed at Phantom Lake Spring. Some possible causes or contributing factors may include:

- Possible cementation or alteration of historical flow paths. This may be because of natural cementation of cavities, sinkhole collapses, or possibly caused by the magnitude 6.0 earthquake centered around Valentine, Texas on August 16, 1931. Since historical geophysical data is scarce or not publicly available, this may be difficult to prove.
- Increase of phreatophytes or other vegetation that is extracting groundwater along the flow path or at the source region of the base flow. As discussed above, any extraction of water from the system may adversely influence water levels at the discharge points.
- Sufficient reduction of recharge during drought or historical climate patterns that causes overall decreases in recharge to the system.

5.0 RECOMMENDATIONS

Insufficient rainfall events occurred during our three-year study to establish the impact of a localized recharge event to the spring system. We recommend a more robust recharge study. This study may include historical climate trends, as well as, monitoring current conditions. Establishing more rain gages throughout the study area at varying elevations may constrain the range of local flows and better define the localized recharge component of the springs. Conducting new stream gain-loss studies of the streams up gradient from Phantom Lake Spring may also help delineate the local recharge area and determine if any changes may have occurred since the 1930s. In addition, we recommend a more thorough investigation of the underlying geology between the Davis Mountains and the discharge area to determine structural impediments to the flow system and the surface water to groundwater relationship.

To observe when recharge is of a sufficient size to influence the flows at the springs, we recommend a continuation of a monitoring program of the springs. Moving the monitoring equipment in Phantom Lake Spring to the main passageway, but far enough away from the submersible pump to avoid interference, may better monitor water conditions at the spring. Water appeared stagnant at the location used and may have been a leading factor in the failure of conductivity parameter of the equipment. If this is not feasible due to the requirement of having a Texas certified cave diver on staff, extending the monitoring of Hamilton windmill is cost-effective alternative.

In addition, staff observed the encroachment of salt cedars near the outlet and historical pool area at Phantom Lake Spring. Salt Cedars (Tamarix ssp) are non-native phreatophytes that can consume as much as 4.15 acre-feet per acre of groundwater per year (2003, Bureau of Reclamation). Controlling or removing the salt cedars may help maintain or at least retard declining water levels observed in Phantom Lake Spring. A larger regional study of the encroachment of phreatopytes in Culberson County and along the Stocks fault may be needed, if additional groves of salt cedars are observed along the proposed base flow path or around the source waters of the springs.

Establishing two continuous stream-flow monitoring sites at each discharge outlet at the San Solomon Springs pool would better serve to establish changes and trends at San Solomon Springs. Current and historical records for this spring monitor flow at only one outlet at a juncture in the canal system that does not capture all the discharge water.

We suggest additional isotope analyses to better delineate the source areas of the springs. At a minimum, we suggest using the same isotopes discussed in this report: Carbon-14 (^{14}C), Carbon-13 to Carbon-12 ($^{13}C/^{12}C$) ratios, Oxygen-18 ($\delta^{18}O$), Deuterium ($\delta^{2}H$), Tritium ($\delta^{3}H$), and Sulfur-34 ($\delta^{34}S$). More wells completed in the Delaware Mountains and the Capitan Reef Complex in the northwest and the west of the springs may need to be included in any future sampling plan in order to observe the spread in the isotope values that may help further constrain the source area.

In addition, we suggest a comprehensive study of the faults and geologic structure in Culberson County. This should include possible flow paths along the western fringe of the Delaware Mountains and eastern section of the Salt Bolsons. The study should also explore the fault system separating or connecting Wild Horse Flats and the Apache Mountains. This study may include installation of nested piezometers along and across dominant fault lines following the flow path to the springs. These dedicated wells should monitor water level fluctuations due to varying rainfall conditions and establish hydraulic communication between the faults and adjacent aquifer materials. A tracer test or series of tracer tests may also provide the same information. A geophysical survey may be helpful in determining if cementation or alteration of flow paths is a possible cause of reduced base flow at the springs.

Monthly or seasonal sampling of the isotopes from the springs may need to be undertaken to record changes in the composition, if any, that may also reflect changes to the source water. We also recommend isotope sampling over larger areas and stratigraphic intervals to further establish geochemical relationships and further constrain the source region of the waters discharging from the springs.

Isotopic sampling of the rainfall from a wider area of the Davis Mountains, Toyah basin, and areas further west may prove useful in developing local meteoric water lines that may be different than those observed from groundwater data. Shifts in between the various local meteoric water lines may lead to additional insight to the source water identification.

The NETPATH correctional models presented herein may be non-unique because the assumptions used for Carbon-14 enrichment factors have significant bearing on the corrected ages. More trial and error runs may be needed to explore other scenarios with regard to the geological conditions that have existed during recharge, also to improve the match between measured and calculated isotope values.

To verify the elevation of benchmark “BSP1” is accurate we recommend a follow up survey. The NGS benchmark used for the Phantom Lake Spring survey in this report is within accuracy range of the GPS equipment used and would be the closest verified, Code “A” benchmark to Balmorhea State Park. We also recommend verifying and possibly further refining the elevation of the temporary benchmark at East Sandia. The closest verified benchmark listed with NGS is identified as BP0520 (V452). It was rated a Code “B” indicating a distribution rate of 1.1 through 2.0 mm/km.

6.0 ACKNOWLEDGMENTS

In any major study, there are many people to acknowledge. We wish to thank Texas Parks and Wildlife and U.S. Fish and Wildlife Service for funding the project. We appreciate the comments and insights provided by the reviewers that included John Ashworth, Dr. Charles Kreitler, Dr. Mathew Uliana, Stefan Schuster, Craig Farquhar, and Nathan Allan. We wish to thank the kind assistance provided by local landowners for allowing access to their properties. In addition, we appreciate the Bureau of Reclamation, Texas Department of Transportation, Reeves County Water Improvement District #1, Jeff Davis County Underground Water Conservation District, and all the staff at Balmorhea State Park for their cooperation. Finally, we wish to thank our management and staff at Texas Water Development Board who contributed to this project.

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8.0 APPENDIX A: FIELD MEASUREMENTS (SPRINGS)

FIELD MEASUREMENTS

Table 18. recorded water levels from staff gage at Phantom Lake Spring outside gate in immediate pool area.

DATE	STAFF GAGE READING	WATER-LEVEL ELEVATION	MEASURED BY
5/23/00	5.45	3475.26	Fish & Wildlife
5/25/00	5.25	3475.06	Fish & Wildlife
6/6/00	4.99	3474.8	Fish & Wildlife
6/15/00	5.02	3474.83	Fish & Wildlife
6/26/00	5.19	3475	Fish & Wildlife
6/28/00	5.12	3474.93	Fish & Wildlife
12/12/00	4.48	3474.29	Fish & Wildlife
2/8/01	4.55	3474.36	TWDB
2/8/01	4.5	3474.31	TWDB
2/9/01	4.42	3474.23	TWDB
2/11/01	4.5	3474.31	Fish & Wildlife
2/27/01	4.48	3474.29	TWDB
3/19/01	4.35	3474.16	Fish & Wildlife
4/16/01	4.38	3474.19	Fish & Wildlife
4/17/01	4.32	3474.13	Fish & Wildlife
4/24/01	4.28	3474.09	TWDB
4/26/01	4.34	3474.15	TWDB
6/11/01	4.28	3474.09	TWDB
9/26/01	3.93	3473.74	TWDB
12/18/01	4.48	3474.29	TWDB
3/21/02	3.74	3473.55	TWDB
5/14/02	3.88	3473.69	TWDB
8/20/02	3.57	3473.38	TWDB
11/19/02	3.6	3473.41	TWDB
1/14/03	3.97	3473.78	TWDB
6/28/03	3.88	3473.69	TWDB

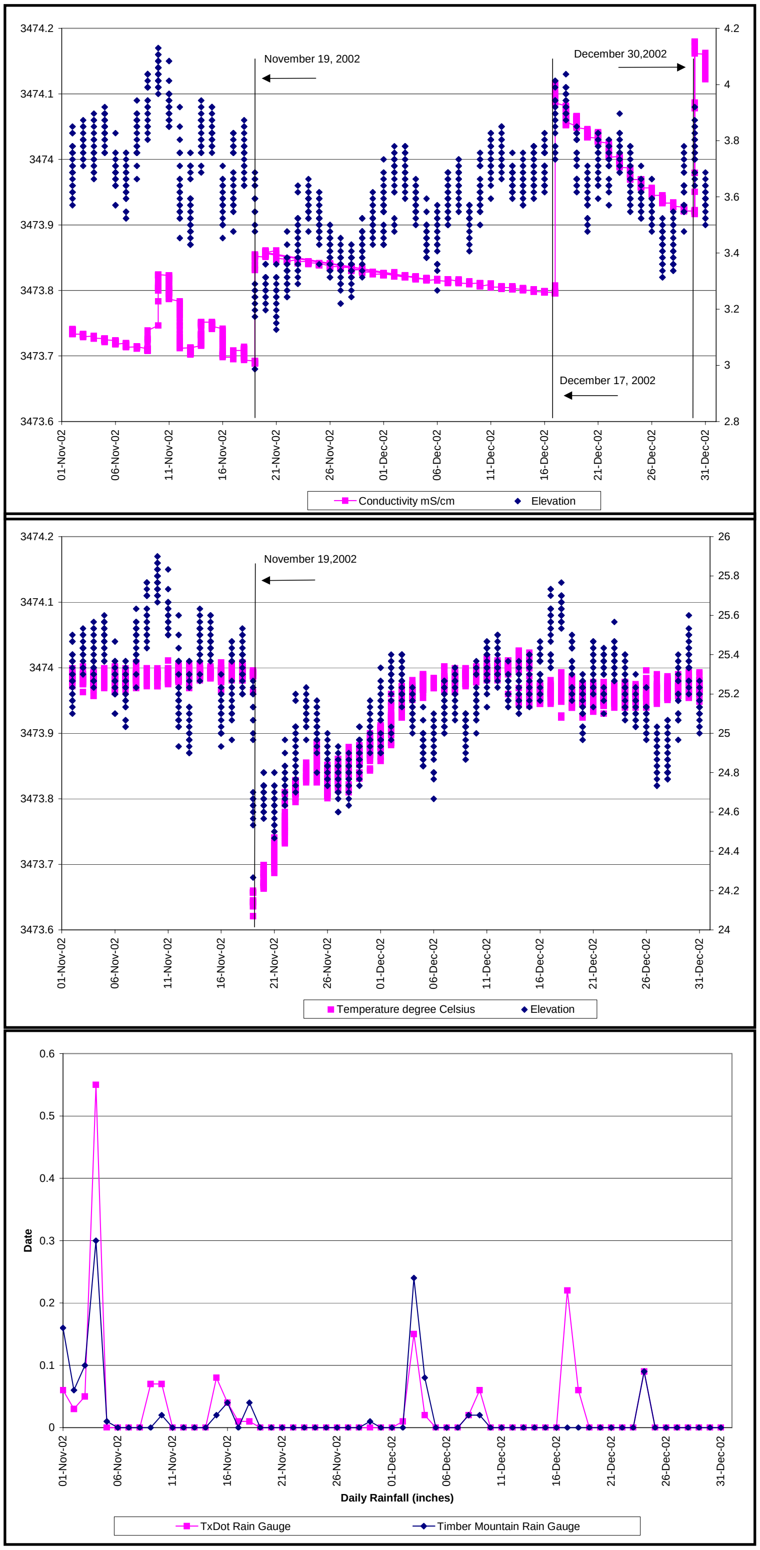

Figure 76. Comparison of water levels at Phantom Lake Spring with conductivity (top graph), Phantom Lake Spring water levels and temperature (middle graph), and daily rainfall from the Timber Mountain and TxDot gauging stations (bottom graph). Detailed data from transducer and datalogger measurements recorded from November 1, 2002 through December 31, 2002.

Table 19. recorded water levels, pH, temperature, an dconductivity from East Sandia, Giffin, San Solomon, and Phantom Lake springs using field equipment.

Spring Name	Texas State ID	Date	Time	Gage	pH	Temp (ºC)	Conductivity	Remarks
East Sandia Spring	52-03-115	2/8/2001	11:17 AM	none	7.19	19.9	4020	TWDB
		8/28/2001	12:58 PM	none	7.8	NR	4070	TWDB
		3/21/2002	10:40 AM	none	7.17	19	4180	at post
		5/14/2002	12:10 PM	none	7.07	20.7	4190	TWDB
		8/20/2002	3:10 PM	2.37	7.19	22.3	4080	TWDB
		11/20/2002	10:18 AM	2.43	7.13	17.7	4430	TWDB
		11/21/2002	9:10 AM	2.42	7.13	18.4	4150	TPWD
		12/9/2002	10:05 AM	2.44	7.44	18	4170	TPWD
		12/16/2002	10:00 AM	2.46	7.15	18.3	4150	TPWD
		12/23/2002	2:15 PM	2.46	7.15	18.2	4220	TPWD
		1/8/2003	10:45 AM	2.46	7.13	18.2	4170	TPWD
		1/14/2003	4:45 PM	2.48	7.26	19.8	4420	TWDB
		1/21/2003	3:20 PM	2.46	7.16	19.6	4420	TPWD
		2/3/2003	3:30 PM	2.46	7.16	19.5	4400	TPWD
		2/10/2003	10:00 AM	2.46	7.62	17.6	4190	TPWD
		2/17/2003	1:35 PM	2.5	7.13	19.6	4290	TPWD
		2/24/2003	11:00 AM	2.48	7.16	19.5	4290	TPWD
		3/6/2003	3:19 PM	2.5	6.96	20.5	4880	TWDB
		3/25/2003	11:00 AM	2.46	7.14	19.4	4170	TPWD
		6/26/2003	12:44 PM	2.4	7.74	20.7	3750	TWDB
Giffin Spring	52-02-610	2/8/2001	10:25 AM	none	7.34	24.2	3360	TWDB
		8/28/2001	1:30 PM	none	7.26	26.7	3390	TWDB
		3/21/2002	11:25 AM	none	7.32	25.5	3390	TWDB
		5/14/2002	11:44 AM	none	7.13	25.5	3390	TWDB
		8/21/2002	1:36 PM	3.77	7.23	25.9	3380	TWDB
		8/21/2002	1:36 PM	3.77	7.23	25.9	3380	TWDB
		11/20/2002	9:35 AM	3.61	7.04	24.7	3510	TWDB
		1/14/2003	4:16 PM	3.54	7.24	25.1	3490	TWDB
		3/6/2003	2:50 PM	3.56	7.08	25.5	3700	TWDB
		6/26/2003	12:24 PM	4.03	7.48	25.8	3260	TWDB
San Solomon Springs	52-02-611	2/8/2001	11:36 AM	NA	7.46	24	3380	TWDB
		8/30/2001	3:09 PM	NA	7.27	26.5	3420	TWDB
		3/21/2002	11:07 AM	NA	7.24	24.8	3420	west end
		5/14/2002	3:00 PM	NA	7.13	25.3	3420	TWDB
		5/14/2002	3:38 PM	NA	NR	25.03	3373	TWDB
		8/20/2002	9:50 AM	NA	7.14	24.6	3420	TWDB
		11/19/2002	9:49 AM	NA	6.93	24.2	4380	TWDB
		11/21/2002	8:32 AM	NA	7.29	23.9	3410	TPWD
		11/25/2002	10:15 AM	NA	7.33	23.9	3410	TPWD
		12/2/2002	9:00 AM	NA	7.34	23.9	3410	TPWD
		12/9/2002	11:00 AM	NA	7.31	23.9	3410	TPWD
		12/23/2002	2:15 PM	NA	7.3	23.9	3410	TPWD

		1/8/2003	9:30 AM	NA	7.29	23.9	3410	TPWD
		1/14/2003	3:00 PM	NA	7.28	24.6	3470	TWDB
		1/21/2003	2:45 PM	NA	7.3	23.9	3410	TPWD
		2/3/2003	3:00 PM	NA	7.06	25	3410	TPWD
		2/10/2003	9:00 AM	NA	7.07	23.9	3480	TPWD
		2/17/2003	11:15 AM	NA	7.03	24.3	3460	TPWD
		2/24/2003	9:00 AM	NA	7.04	23.9	3460	TPWD
		3/3/2003	3:48 PM	NA	7.1	24.9	3700	DO=3.94
		3/6/2003	12:15 PM	NA	NR	23.63	3718	TWDB
		6/26/2003	8:25 AM	NA	7.33	24.9	3140	DO=1.93
Phantom Lake Springs	52-02-405	2/8/2001	NR	4.55	6.85	24.5	3530	
		8/28/2001	10:30 AM	NR	7.21	25.3	3570	
		9/26/2001	1:09 PM	3.93	7.11	25.1	3540	
		12/18/2001	NR	4.48	NR	24.7	3540	
		5/14/2002	10:00 AM	3.88	7.19	25.1	3530	
		8/20/2002	10:00 AM	3.57	7.18	25.4	3530	
		11/19/2002	5:00 PM	3.6	7.04	24.9	4110	
		1/14/2003	12:48 PM	3.97	7.25	25.1	3590	
		3/3/2003	3:00 PM	NR	7.11	25	3710	
		3/6/2003	12:53 PM	NR	NR	23.83	3470	
		6/26/2003	9:31 AM	3.88	7.79	25.2	3310	