USING MAJOR ANIONS AND CATIONS TO DESCRIBE TRANS-PECOS SPRINGS

THESIS

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CHAPTER I

INTRODUCTION

Groundwater is an important source of water supply throughout the world. It is used in industry, agriculture, municipalities, rural homes and other aspects of our lives (Todd 1980). The United States Geological Survey (USGS) reported groundwater withdrawals in the United States at 2.73 x 10^8 m^3 per day in 1985 and 3.14 x 10^8 m^3 per day in the year 2000. One of the main uses of groundwater in the United States is irrigation. Historically, more surface water than groundwater has been used for irrigation. However, in the past 50 years the use of groundwater for irrigation using groundwater has increased, and in 2000 estimated groundwater use for agriculture in the United States was 1.29 x 10^8 m^3 per day (Hutson et al. 2004).

Texas relies heavily on groundwater as a freshwater source. Total groundwater use in Texas in 1975 was 4.27 x 10^7 m^3 per day and constituted 73 percent of total water use (Murray and Reeves 1977). In 1999, the Texas Water Development Board (TWDB) estimated total groundwater use at 3.14 x 10^7 m^3 per day. About 78 percent of the 3.14 x 10^7 m^3 per day was used for irrigation (Madden and Pederson 2002). In 2000, the USGS estimated groundwater use in Texas within five main areas - industry, irrigation, livestock, mining, and thermoelectric - with a total consumption of 2.68 x 10^7 m^3 per day, and approximately 90 percent of this being used for irrigation. The TWDB, whose function is to oversee the conservation and development of water for Texas, has prepared two reports on selected areas of the Trans-Pecos region in Texas. Report 317 (Ashworth 1990) was prepared in response to Senate Bill 2 (passed in 1985). This bill focused on addressing areas of the state where groundwater quantity and quality were deteriorating. Report 348 (Boghici et al. 1999) was in response to Senate Bill 1 (passed in 1997). This bill focused on the identification of areas in the state experiencing or expected to experience water problems within the subsequent 25-year period. The study looked at physical and chemical changes that have occurred in the region's water supply between 1988 and 1998 (Boghici et al. 1999).

The importance of water in Texas has grown substantially in recent years due to population increases and drought. West Texas (Trans-Pecos) is no exception, and compared to many other geographic regions in Texas, is most heavily dependant upon groundwater. Groundwater and spring discharge are a main source of freshwater in this region due to limited precipitation and scarcity of surface water (Uliana and Sharp 2001).

El Paso currently relies on groundwater for about half of its water supply and Ciudad Juarez, Mexico relies entirely on groundwater from the Hueco Bolson aquifer (Mace 2001). Both cities are quickly depleting their fresh groundwater resources and it is estimated both cities will pump the last of their groundwater resource by 2020 (Washington and Perez 2001). Also, springs in the Trans-Pecos are important sources of water to small communities and ranches. Farmers use discharge from San Solomon Spring for irrigating their crops. Springs such as San Solomon and Hot Springs (Big Bend) have aesthetic and recreational value as well. The springs also provide habitat for several endangered species and other wildlife that are unique to this region of the state

(Mace 2001). Adverse impacts to groundwater systems can already be seen at Kokernot Spring, Phantom Lake Spring and Commanche Spring. These springs have ceased flowing except following large rain events. As local groundwater resources decline, these cities will begin to look for water sources in other areas.

In recent years proposals, for increased groundwater withdrawals in the Rio Grande basin has created discussions on water quality, economic viability and sustainability. One project proposed by Rio Nuevo Ltd., Midland, Texas, involves pumping from 355,000 acres of land from Hudspeth, Jeff Davis, Presidio and Culberson counties (Friedberg 2003). These discussions have been heated because limited data on wells, springs and aquifer systems in the Trans-Pecos region have made sustainability predictions difficult. A few aquifers (Hueco-Mesilla Bolson, the Cenozoic Pecos Alluvium, the Edwards-Trinity, and Bone Spring-Victorio Peak) have been studied extensively. However, other aquifers (Capitan Reef, Dockum, Igneous, Marathon, Rustler, and West Texas Bolsons) have had little to almost no attention given to them (Mace 2001).

The goals of this study are to provide detailed water quality data for springs found in the Trans-Pecos region of Texas. Also this study will classify the sampled springs based on their dominant water type and identify their groundwater sources using major anion and cation data. This information will improve baseline data on the springs of the Trans-Pecos region. The water quality data will be submitted to the TWDB for their groundwater database. In the future, this water quality data will be available for policy decisions and management plans made in the Trans-Pecos region.

Description of the Area

The Trans-Pecos is the region west of the Pecos River, bounded by the Rio Grande on the south and west, and by the thirty-second parallel on the north (Fig. 1). The Trans-Pecos covers approximately 11 % of Texas and, because of its great distance from major population centers; this area is probably the least known portion of the nation's second largest state (Schmidt 1995). This region is made up of Mountains, grasslands, desert and basins. Ground elevation ranges from 700 m above sea level to 2667 m above sea level (Fig. 2). The Trans-Pecos region lies within the northern portion of the

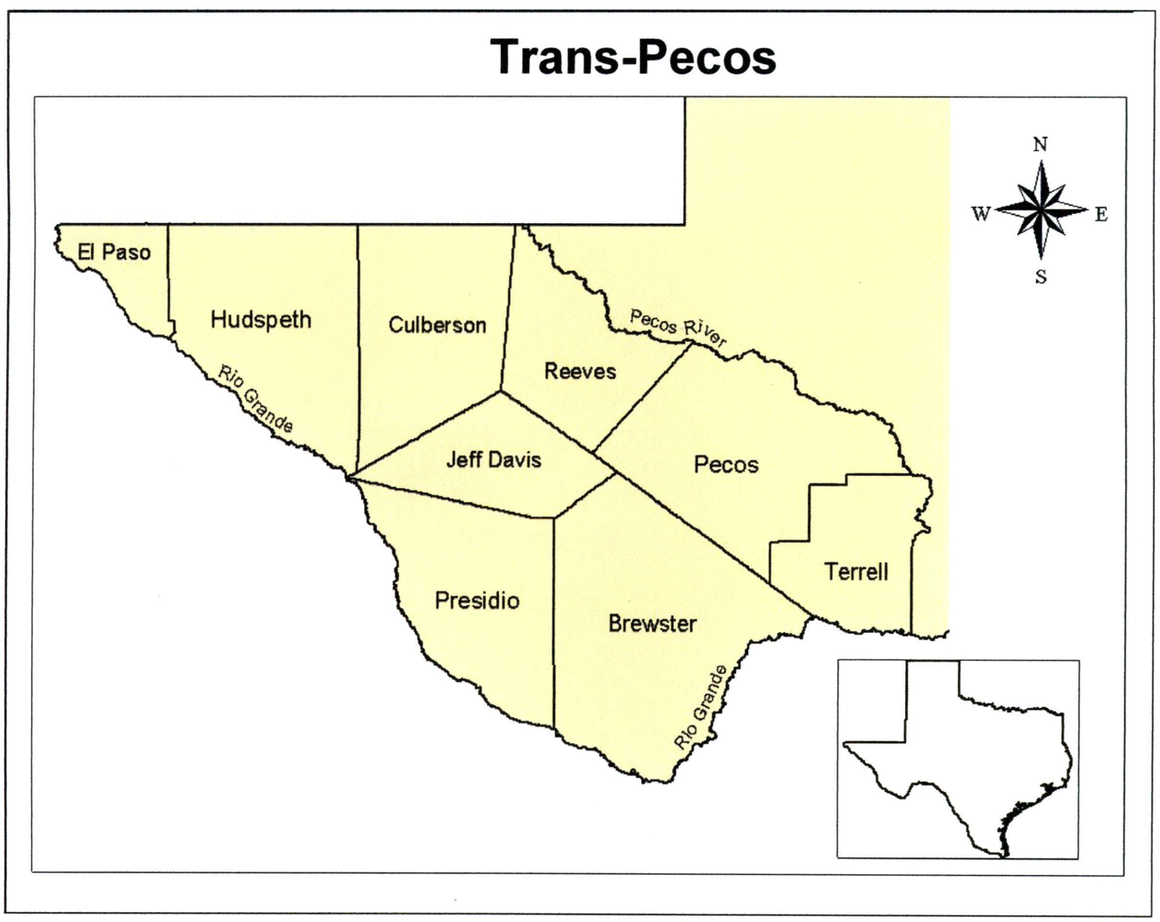

Fig. 1. Trans-Pecos Region

Chihuahuan Desert, a 1,900-km long and 1290-km wide arid zone that extends southward into Mexico. The Trans-Pecos region of Texas is a subtropical arid climate with an annual rainfall of approximately 30 cm (Fig. 3). The highest altitudes and the eastern most edge of the Trans-Pecos are the only areas that receive enough precipitation to be considered semiarid instead of true desert (Schmidt 1995). The climate for Jeff Davis County and adjoining areas of Brewster and Presidio Counties, range from cool-humid temperatures at elevations above 1,200 m to arid-subtropical at lower elevations. Rainfall during the spring and summer months is dominated by widely scattered thunderstorms. Because of the vertical developing of thunderstorms and orographic lifting effect of mountain areas, the amount of spring and summer precipitation increases with elevation (LBG-Guyton Associates 2001).

The Rio Grande, Rio Conchos and the Pecos River provide most of the water flow in this region. The area is typified by internal drainage basins, which provide some recharge to the aquifers. Most researchers believe that recharge in the Trans-Pecos is approximately one percent of the annual precipitation. However, some estimates claim that recharge varies from one to five percent of the annual precipitation. In the Trans-Pecos, the rate of recharge does not necessarily increase with elevation. Recharge is dependant more on the watershed characteristics, surface geology and feasibility of surface water to enter the ground-water system (Bennett 2002).

Geology Overview of the Study Area

The Big Bend area is known to have some of the most geologically complex and diverse terrain found in Texas. These geologic formations have significant impacts on

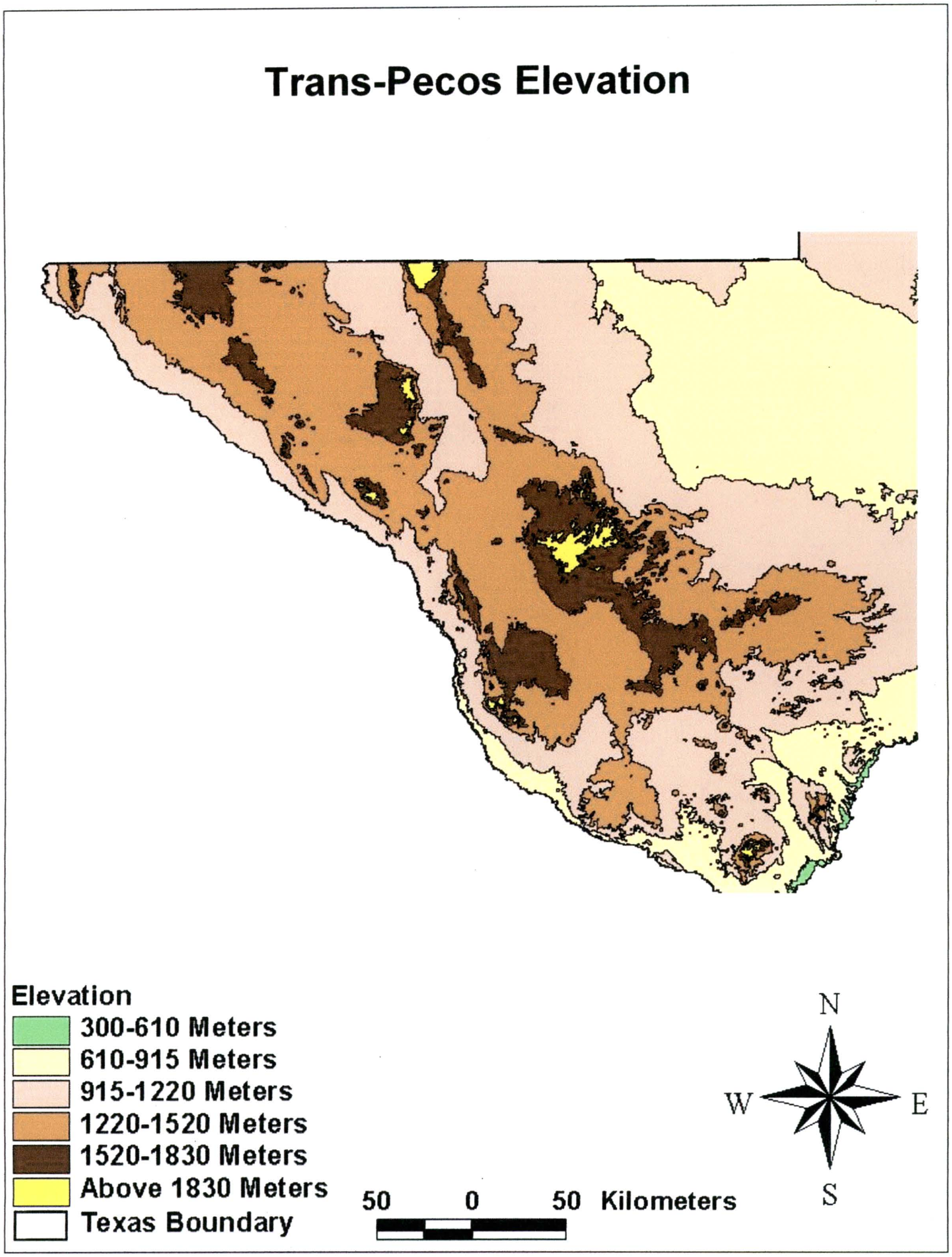

Fig. 2. Trans-Pecos Elevation.

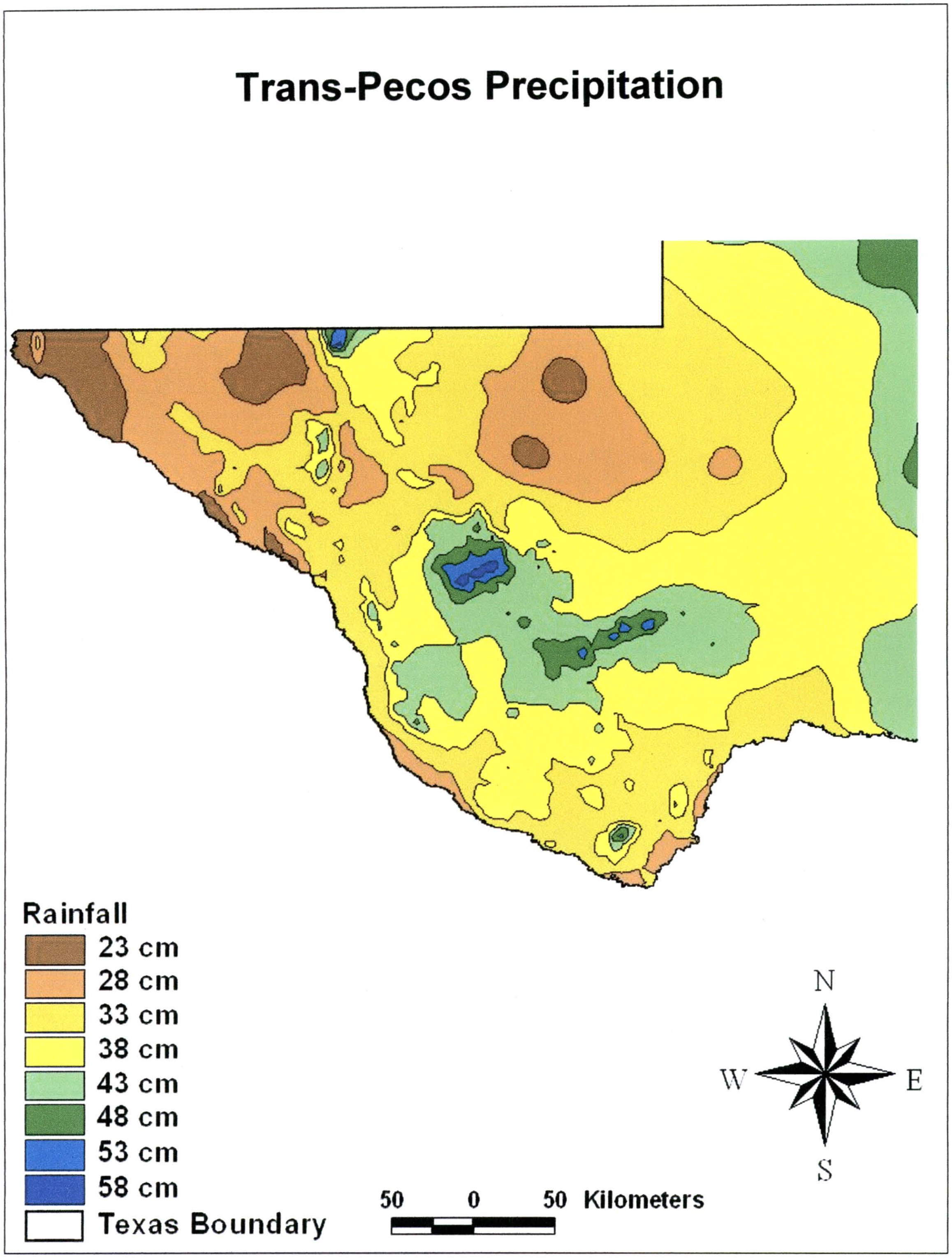

Fig. 3. Trans-Pecos Precipitation (TWDB Avg. from 1961-1990).

the water chemistry in local aquifers. Geologic formations found in these parks include present day wind blown sand dunes to 500 million year old rocks. There are several important time periods represented in the rocks of the Big Bend region. One of the earliest occurred approximately 300 millions years ago. During this period the Ouachita Mountains rose as a result from the collision of two continents. Also as a result of this collision several basins formed which filled with sea water and sediments. This fill included marine limestone in addition to transitional and fluvial gravel, sands and clays. During the Cretaceous period, approximately 100 million years ago, a warm shallow sea deposited limestone and mud over the Big Bend region. Then during the Cenozoic, fluvial and coastal sediments were deposited as the sea receded to its present day location. These layers are located in lowlands surrounding the Chisos Mountains. Also, volcanic eruptions during the Eocene and Oligocene resulted in the deposition of large amounts of lava and ash (Spearing 1991).

The Davis Mountains are located in Jeff Davis County and are the second highest range in Texas. These mountains were formed during violent volcanic activity approximately 35 million years ago (Spearing 1991). Various horizontally bedded volcanic strata make up this mountain range. Thick ash-flow tuffs are the most common strata found in the Davis Mountains but felsic lavas and basalts are also present (Uliana et al. 2006). The magma came from two main volcanic centers, the Paisano Volcano and the Buckhorn Caldera (Spearing 1991).

The Guadalupe Mountains are located in Culberson County and have the highest peak in Texas, El Capitan. These mountains are part of an ancient marine fossil reef known as the Capitan Reef (Ashworth and Hopkins 1995). The reef was formed approximately 250 million years ago during the Permian Period. During this period, colonial marine organisms formed a 400-mile long horseshoe-shaped reef. At the end of the Permian period the ocean receded creating a lagoon in which extensive evaporite deposits covered the basin (Uliana and Sharp 2001). Over millions of years the ocean receded and streams deposited sediments over the reef until a mountain-building uplift, approximately 70 millions ago, in this region exposed part of the fossil reef. Then approximately 10 million years ago an extension of this mountain building episode uplifted the deeply buried reef. This uplift along with intense erosion helped to carve and mold the mountains we see today (Spearing 1991).

Groundwater of the Trans-Pecos

Aquifer systems located in the Trans-Pecos study area consist of two major aquifers: the Edward's-Trinity and the Cenozoic Alluvium (Fig. 4) and several minor aquifers: the Bone Spring-Victorio Peak, Capitan Reef Complex, Dockum, Igneous, Marathon, Rustler and the West Texas Bolsons (Fig. 5).

The Cenozoic Alluvium aquifer is a deep accumulation of alluvial sediments washed into intermontane (valley) areas from surrounding highlands (Price et al. 1989). There are two hydrologically separate basins, the Pecos Trough in the west and the Monument Draw Trough in the east. The main source of recharge for these aquifers is precipitation and in some cases losses from the Pecos River. High withdrawal rates from these aquifers for irrigation have caused groundwater levels to drop, therefore allowing water from the Pecos River to recharge the aquifers (Ashworth and Hopkins 1995). This could account for high levels of total dissolved solids (TDS),

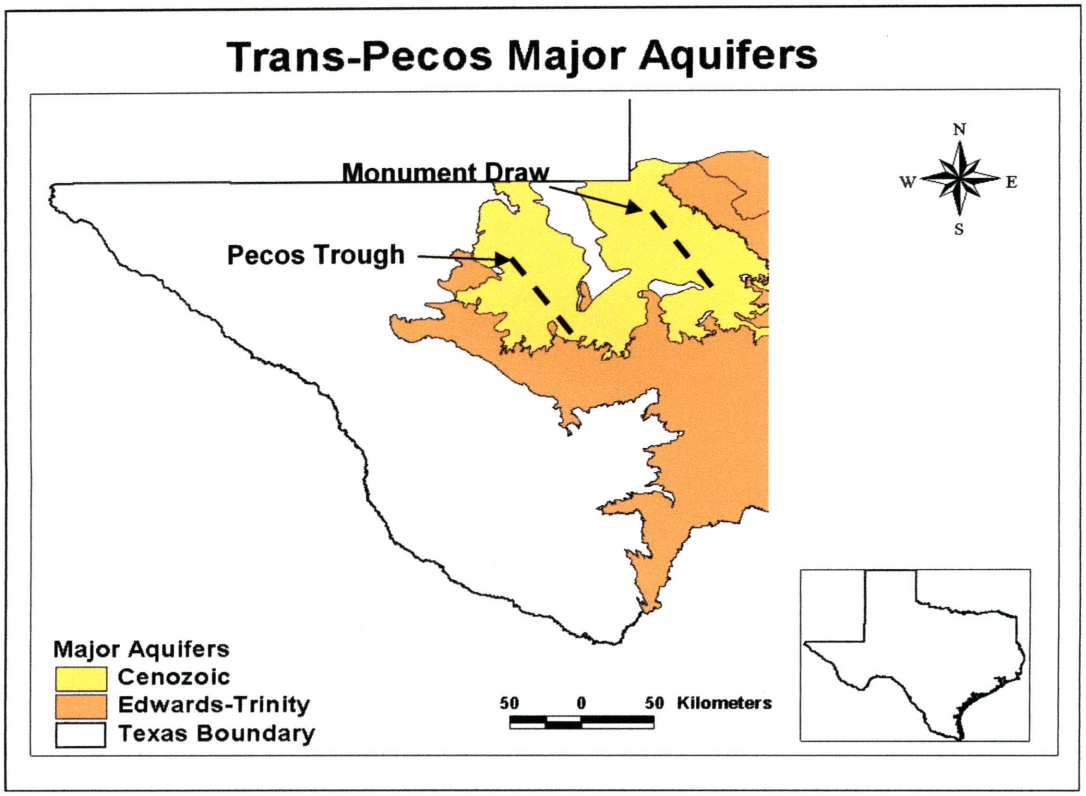

Fig. 4. Major Aquifers Found in the Trans-Pecos.

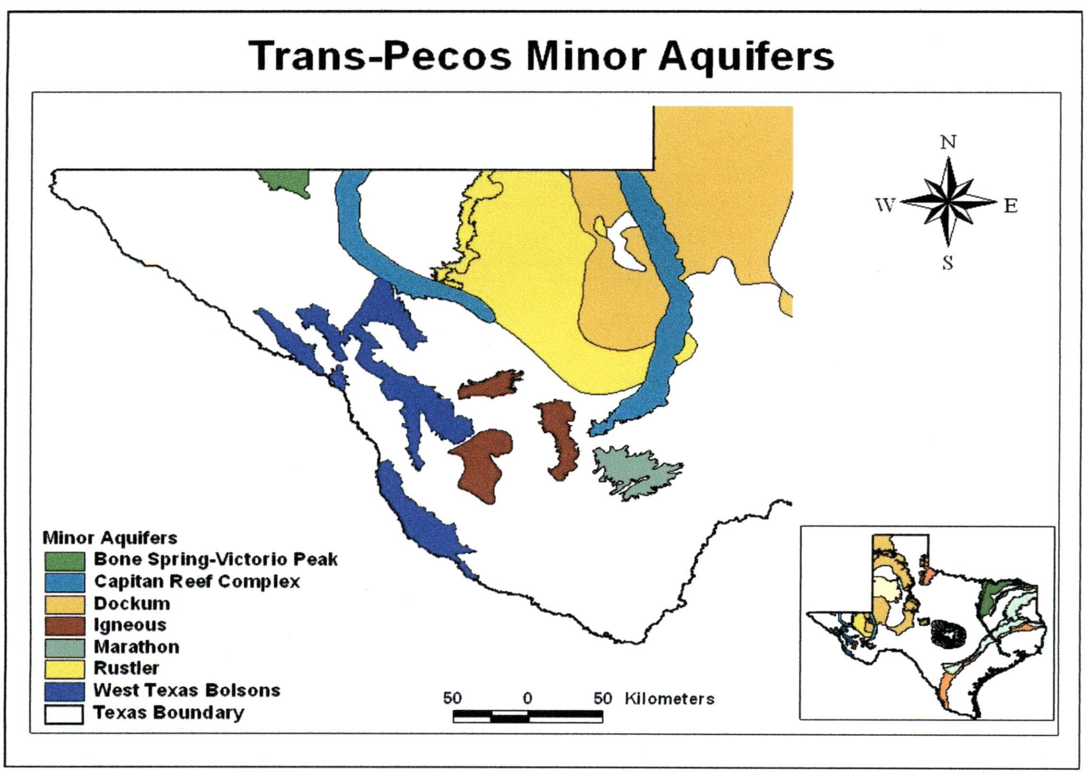

Fig. 5. Minor Aquifers Found in the Trans-Pecos.

chlorides (Cl) and sulfates (SO_4) found in these aquifers. Also, brine water from irrigation return is known to occur in the area and could contribute to the high levels of TDS, Cl and SO_4.

Groundwater from Edward's-Trinity aquifer has a wide range of TDS and is typically hard consisting mostly of calcium (Ca) and bicarbonate (HCO_3). The salinity of the groundwater tends to increase towards the west with some areas having unacceptable levels of fluoride (Hopkins 1995).

The Igneous aquifer system is made up of fractured lava flows, tuffs and other igneous rocks. This system consists of fresh to moderate saline water and supplies several towns in Brewster and Presidio counties.

Groundwater from the Marathon aquifer is found in crevices, joints and cavities within the limestone and is close to the land surface. This is a shallow system and the water is generally hard with TDS ranging from 500 mg/l to 1000 mg/l (Price et al. 1989).

The Bone Spring-Victorio Peak aquifer is composed of limestone, and water quality ranges from 1000 mg/l to 8000 mg/l TDS (Muller and Price 1979). Withdrawals are usually for irrigation because water quality typically does not meet drinking water standards. A deterioration of groundwater has occurred due to salts leaching from irrigated soils (Ashworth 1995).

The Capitan Reef Complex is made up of limestone, dolomite and talus. Water quality west of the Guadalupe Mountains has high concentrations of TDS consisting mainly of Ca, SO_4 and HCO_3 due to salt deposits in the area (Price et al. 1989). The Rulster aquifer, located to the East-Southeast of the Guadalupe Mountains has Ca-SO_4 dominated water due mainly to evaporite deposits (Uliana and Sharp 2001).

The Dockum system, known as the red beds, consists of sand and conglomerate interbedded with layers of terrestrial silt and shale. TDS concentrations range from 1000 mg/l to 20,000 mg/l with high sodium (Na) concentrations.

The West Texas Bolsons aquifer consists of several basins made up of erosional material. The main basins are the Red Light Draw, Eagle Flat, Green River Valley, Presidio-Redford, and the Salt basin. Each basin differs based on the material eroded from the adjacent highlands. Basin materials include coarse-grained volcanics, limestone, silt and clay. The groundwater ranges from fresh to slightly saline (Ashworth and Hopkins 1995).

CHAPTER II

METHODS

A study of the chemical composition of spring water in the Trans-Pecos region of Texas was initiated on July 1st of 2004 (Fig. 6). Thirty-five Trans-Pecos springs were sampled through July of 2005. Springs found in close proximity to one another

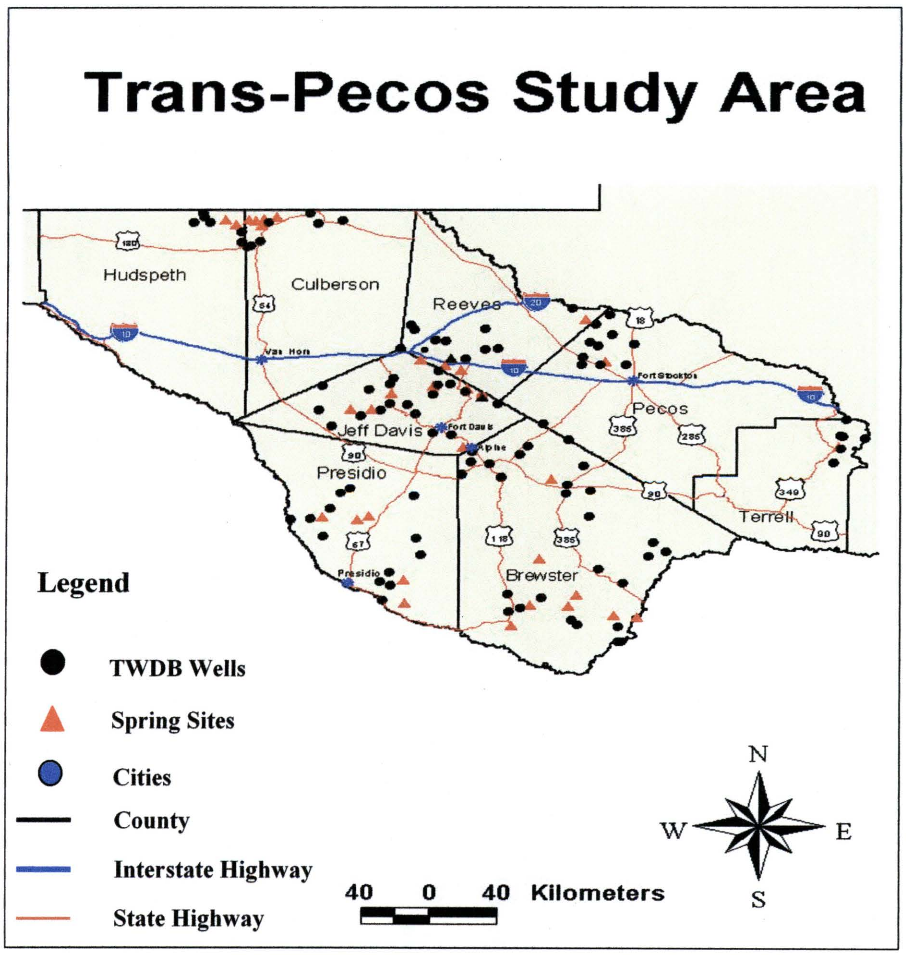

Fig. 6. Study Area with Spring Sites and TWDB Well Sites.

were excluded to decrease multiple sampling of the same ground water source.

Flowing springs were sampled. Each spring was sampled at the discharge point or as close to the source as possible. The Trans-Pecos springs were sampled using TCEQ approved methods for grab sampling (Huston, Marquez, and Baker 1999). Field parameters and chemical parameters measured are shown in tables 1 and 2.

Table 1. Field Parameters Measured.

Field Parameters	
Air Temperature (°C)	pH
Water Temperature (°C)	Specific Conductance (µs/cm)

Table 2. Chemical Parameters Analyzed with Analytical Methods.

Parameter	Methods	Parameter	Methods
Total Alkalinity	SM2320B	Sodium	SM311B
Total Dissolved Solids	EPA160.1	Potassium	SM311B
Silica	EPA370.1	Magnesium	SM311B
Chlorides	EPA325.3	Iron	SM311B
Sulfates	EPA375.4	Aluminum	SM3113
Nitrate, Nitrogen	EPA353.2	Arsenic	SM3113
Nitrite, Nitrogen	EPA353.2	Chromium	SM3113
Fluoride	EPA340.2	Lead	SM3113
Bromide	EPA300	Manganese	SM3113
Total Hardness	Calculated	Selenium	SM3113
Total Phosphorus	EPA365.2	Silver	SM3113
Calcium	SM311B		

At each spring, three water samples were taken using plastic sample bottles. Pretreated nutrient and metal water samples were collected in 500mL plastic containers. Major anions (sulfate (SO_4), chlorides (Cl), bicarbonate (HCO_3)) and cations (calcium (Ca), sodium (Na), potassium (K), magnesium (Mg)) water samples were collected in a non-treated 1.89 L plastic container. The water samples were filled in a manner to reduce sediment disturbance in the spring. The samples were filled until the water reached the neck of the sample bottle to avoid acid loss.

Air temperature at the site was measured using a hand air thermometer. Site descriptions and weather conditions were recorded on field data sheets. Field water analysis was collected with a YSI and/or a Hydrolab probe. The YSI probe (or Hydrolab) was calibrated before each sampling trip. The dissolved oxygen, conductivity and pH probes were calibrated separately using approved chemical standards. Prior to use the probe was checked against approved chemical standards and re-calibrated if necessary. The probe was placed in the same location from which water samples were taken. The probe was given approximately five minutes to equilibrate before measurements were recorded. This allowed for initial water disturbance to clear so that a more accurate reading could be taken.

Several parameters had chemical concentrations below the detection limit, creating problems for some of the subsequent analysis. A simple data transformation used by the EPA was applied to these. This transformation was developed for the chemical analysis of dredged sediments (Jones and Clarke 2005). This transformation was encouraged over more complex transformations for small sample sizes ($n>10$). The specific method used called for the replacement of one-half the detection limit (Clarke 1998).

The spring data was compiled into a database. Boron (B), mercury (Hg), thallium (Tl) and strontium (Sr) were excluded from all analysis. Analysis resulted in concentrations below detection limit for these parameters. The water chemical data for springs sampled more than once were averaged to get a single data set for each spring site (Appendices 1&2).

The TWDB well database was compiled from an electronic groundwater database available at the TWDB website. This database consists of the same chemical parameters as the spring data set, and includes all wells within Texas Boundaries that are presently known by the TWDB. The TWDB data were reduced to focus on specific groundwater locations and parameters relevant to this study. The first reduction removed all TWDB data outside the counties covered in this study. The second reduction removed all wells that did not contain a full balanced set of anion and cation concentrations. Third, the well's latitude and longitude were used to project well sites onto a map using Arcview 3.3 allowing well sites to be chosen based on relative proximity to sampled spring sites.

Water chemical data were analyzed using the Aquachem 4.0 software package to characterize sampled springs and TWDB wells based on major anions and cations. This software was used to create Piper trilinear diagrams and Stiff diagrams of the spring and TWDB data. The Piper trilinear diagram illustrates the relative percent concentrations of major anions, cations and TDS in the water. In the Stiff Diagram, major ion concentrations are plotted horizontally in milliequivalents (Fetter 1988). Stiff diagrams of the TWDB data were created and projected onto the spring sites map to show the general water chemistry for each area (Fig. 7). Stiff diagrams were also created for the spring data and posted on the same map for initial groundwater source classifications to be made.

The sampled springs were divided into regions (Fig. 8) based on geographic location. A principal component analysis (PCA) was run to provide support for the Piper

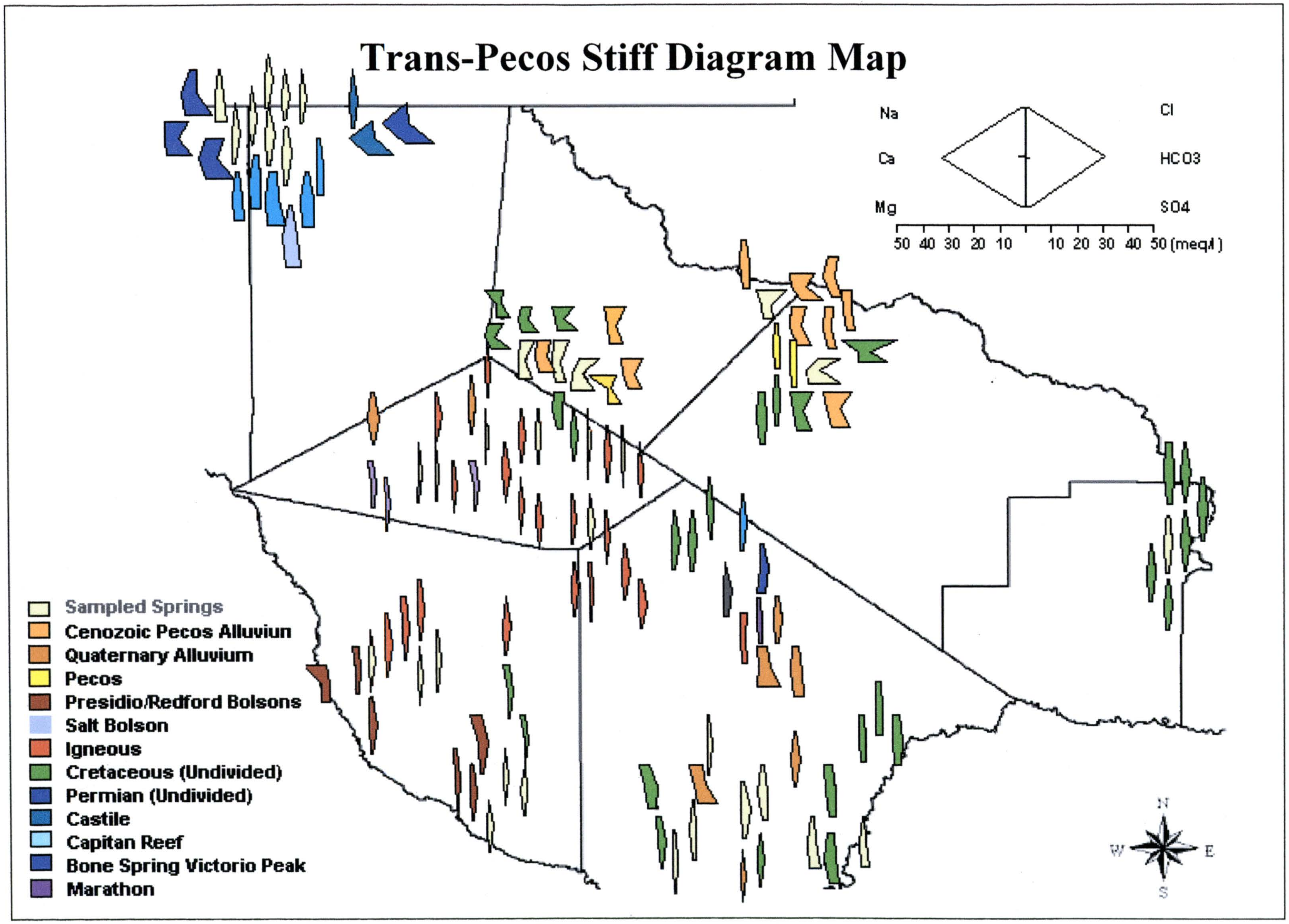

Fig. 7. Stiff Diagram Map. Illustrates major anion and cation concentrations for TWDB wells and sampled springs.

and Stiff diagrams used to classify springs and identify groundwater sources. A PCA involves a mathematical procedure that transforms a number of (possibly) correlated variables into a (smaller) number of uncorrelated variables called *principal components*. The first principal component accounts for as much of the variability in the data as possible, and each succeeding component accounts for as much of the remaining variability as possible (Tauler et al. 2000).

TDS, Na, Cl, Ca, Mg, K, SO_4, HCO_3, Br, F, Si, NO_3 and pH were used in the PCA analysis. All original data after the detection limit data transformation were standardized using z-scores (Williams and Bonner 2006). For the purpose of the PCA; Kokernot Spring, Limpia Spring, Bridge Spring, Tobe Spring, Head Spring, Headquarter Spring and Boar Spring were included in the Davis Mountain grouping. Two PCA were run on the spring dataset. The first PCA included all sampled springs. San Solomon Spring, Phantom Spring, East Sandia Spring, Diamond Y and Santa Rosa Spring were removed from the second PCA.

CHAPTER III

RESULTS

West Texas springs consisted of two distinct groups: a saline group with a mean TDS (±SD) of 3,172 ± 1,594 mg/L (San Solomon Spring, East Sandia Spring, Santa Rosa Spring, Diamond Y Spring and Phantom Spring and a freshwater group with a mean TDS of 367 ± 179 mg/L (Big Bend National Park, Big Bend State Park, Guadalupe Mountains National Park, Cibolo Ranch, Post-Caroline, Davis Mountains; included Seven Spring Ranch and Kokernot Spring). Associated with high levels of TDS, the saline group had greater mean concentrations of Cl, SO_4, Ca, Na and Mg than the fresh water group (Table 3). Water quality and physical attributes of each spring are listed Appendix 1.

Trace metal concentrations were slightly greater than detectable limits or below detectable limits. Among all springs, the maximum concentrations were as follows; Fe, 1.605 mg/L; Al, 0.808 mg/L; As, 0.026 mg/L; Cr, 0.200 mg/L; Pb, 0.010 mg/L; Mn, 0.173 mg/L; Se; 0.059 mg/L; Ag, 0.250 mg/L; Total P, 0.330 mg/L; Nitrite, N; <0.1 mg/L. Mean concentration by spring are listed in Appendices 2.

PCA

The first three PCA axes of the first PCA model using all the springs explained 73% of the total variation in dataset (Table 4). The first PCA axis (51% of the total variation) described the TDS gradient (Fig. 9). TDS (0.3837), Cl (0.3757), Ca (0.3710)

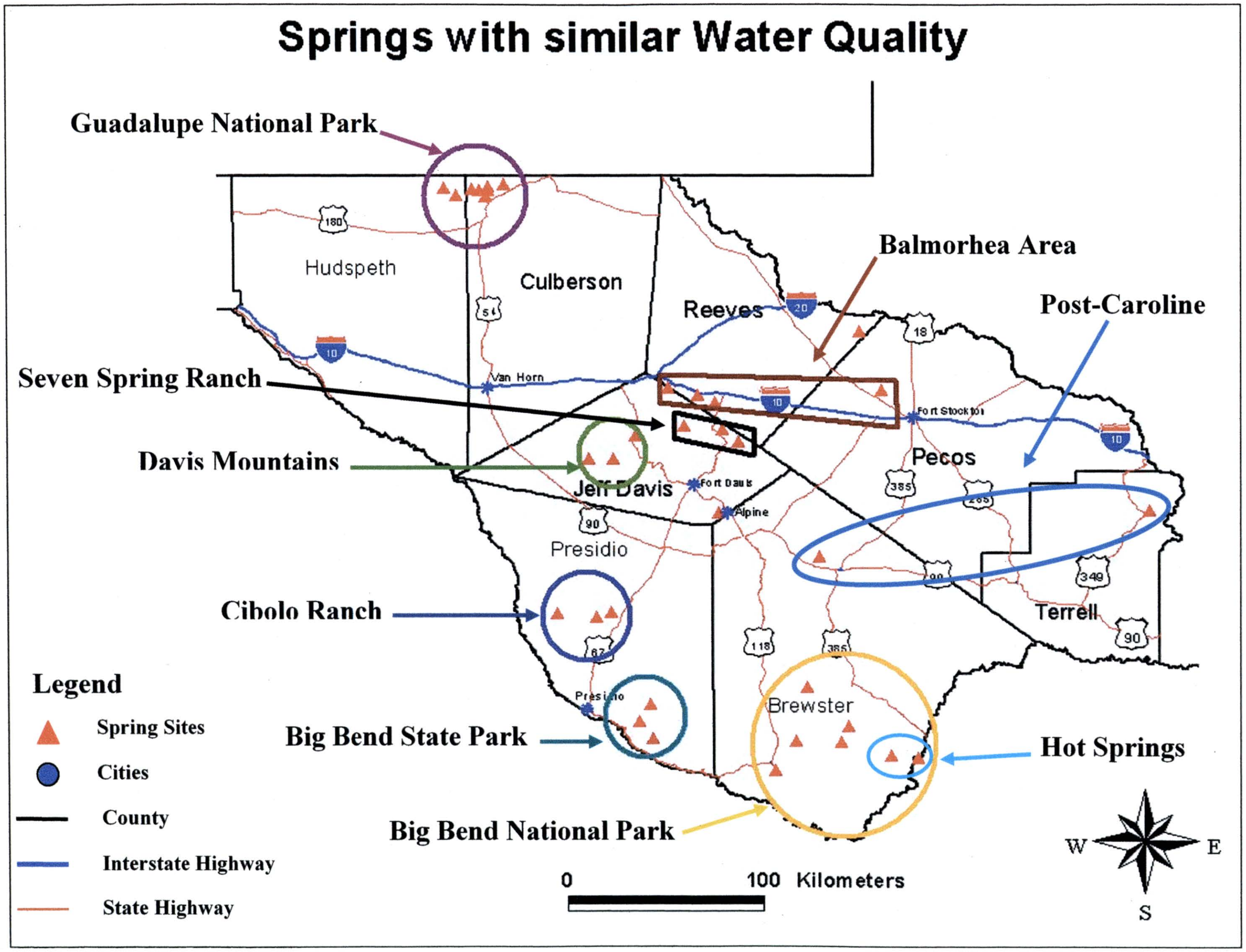

Fig. 8. Regional Groupings.

Table 3. Descriptive Statistics for Parameters Used in PCA and Water Quality Analysis (Saline Group).

	TDS (mg/L)	HCO_3 (mg/L)	Cl (mg/L)	SO_4 (mg/L)	Ca (mg/L)	Na (mg/L)	K (mg/L)	Mg (mg/L)	Si (mg/L)	NO_3 (mg/L)	F (mg/L)	Br (mg/L)	pH
Saline Group													
Min	1465	188	377	220	101	2 9	12 0	9 0	9 4	0 2	1 2	0 3	6 0
Max	5685	304	1638	2305	480	533	22 9	320 0	43 6	6 5	2 4	2 0	7 1
Mean	3157	234 1	905	959	215	103	18 1	114 1	24 0	2 1	1 8	1	6 5
Stdev	1594	39 4	442	729	128	170	3 3	106	11	2 3	0 3	1	0 4
Freshwater Group													
Min	105	34	5	5	11 2	1 5	0 3	1 3	2 4	0 05	0 1	0.03	5 6
Max	915	366	72	365	151 8	82 2	12 5	66 3	59 2	3 20	4 4	0 34	12 5
Mean	367	221 0	13 5	58 9	50 3	13 8	4 1	17 2	22 3	0 77	1 2	0 11	6 9
Stdev	179	71 9	19 3	91 1	26 0	17 4	2 9	13 8	19 5	0 76	1 2	0 10	1 0

and SO_4 (0.3572) had the highest positive loadings on PCA axis 1, and pH (-0.0394) was the only parameter with a negative loading on PCA axis 1. The second PCA axis (11% of the total variation) described HCO_3 (0.5560) and pH (0.5788) having the highest positive loadings and Si (-0.5565) having the highest negative loading. The third PCA axis (11% of the total variation) described Na (0.6164) and F (0.4583) having the highest positive loadings, and NO_3 (-0.3279) and SO_4 (-0.2071) having the highest negative loadings.

Table 4. First PCA Model Loadings and % Variance Explained by Parameters.

	PCA		
Parameter	1	2	3
Br	**0.3667**	-0 0163	0 0372
Ca	**0.3710**	0 0908	-0.1017
Cl	**0.3757**	-0 0518	-0 0288
F	0 1213	0 0110	**0.4583**
HCO_3	0 0913	**0.5560**	-0.1323
K	0 2891	-0 0245	0.3979
Mg	0 3235	0 0793	-0 2068
Na	0 1690	0 1062	**0.6164**
NO_3	0 2618	-0.1225	**-0.3279**
pH	**-0.0394**	**0.5788**	0.1067
Si	0 0436	**-0.5565**	0.1306
SO_4	**0.3572**	-0.0398	**-0.2071**
TDS	**0.3837**	-0 0092	-0.0068
% Variance Explained	51	11	11

Springs positively associated with PCA axis 1 were Hot Springs #5 (0.3146), HotSprings Rio (0.1478) and Mckinney Spring (0.1875) and springs found in the Balmorhea Area (5.306) (Fig. 9). Springs negatively associated with PCA axis 1 were Burro Spring (-0.1483), Buttrill Spring (-1.108), Glenn Spring (-0.3631), Oak Spring (-0.9301), springs found in the Davis Mountains (-1.289), Cibolo Ranch (-0.9983), Post-Caroline (-0.3292), Big Bend State Park (-0.9871) and Guadalupe Mountains National Park (-1.078).

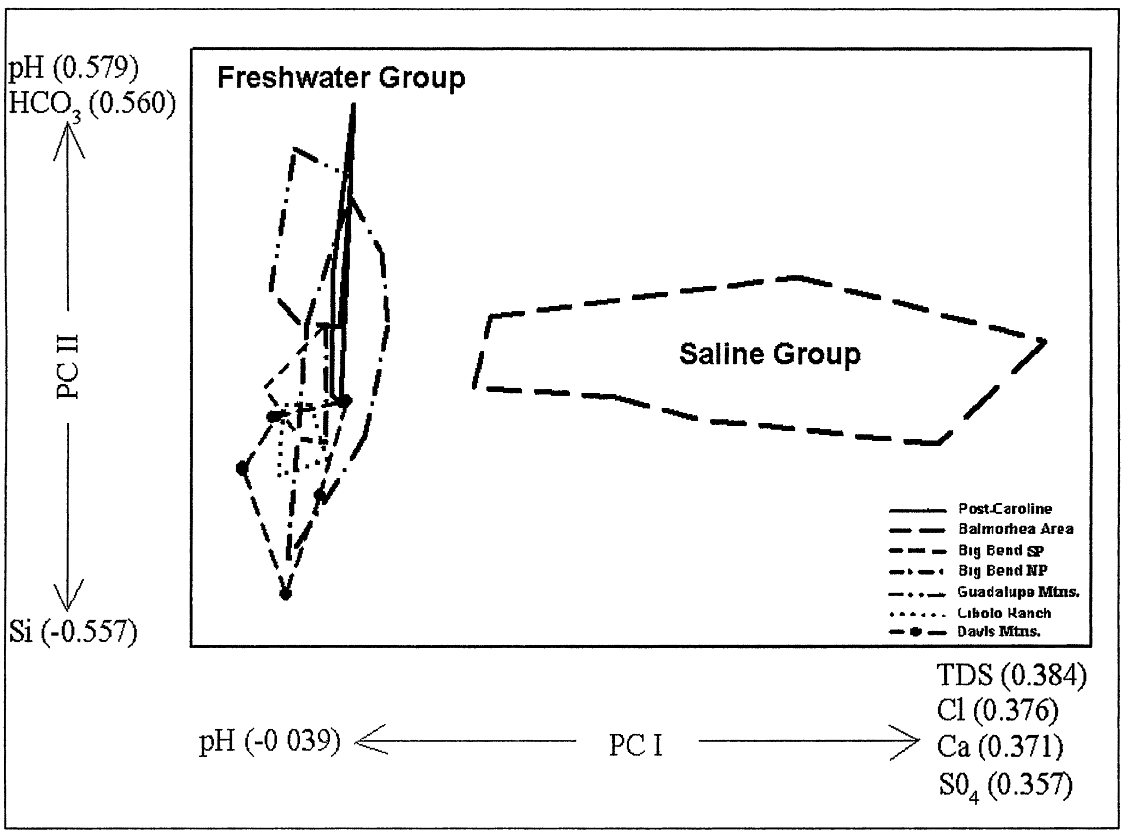

Fig. 9. The First PCA Model. The 1st and 2nd principal components are shown.

Springs positively associated with PCA axis 2 were Post Spring (1.865), Burro Spring (0.0795), Glenn Spring (1.454), Mckinney Spring (0.0650), Oak Spring (0.1880), Phantom Spring (0.3734), Santa Rosa Spring (0.8191) and springs found in Guadalupe

Mountains National Park (1.146). Springs negatively associated with PCA axis 2 were Las Cuevas Spring (-0.6313), Smith House Spring (-1.004), Buttrill Spring (-1.822), Caroline Spring (-0.4773), East Sandia Spring (-0.7052) and springs found in Cibolo Ranch (-1.113) and the Davis Mountains (-1.497).

Springs positively associated with PCA axis 3 were Santa Rosa Spring (4.536) and San Solomon Spring (1.852), Phantom Spring (1.668), Post Spring (0.3689) and springs found in Big Bend National Park (0.9603), Big Bend State Park (0.3836) and Cibolo Ranch (0.1464) (Fig. 10). Springs negatively associated with PCA axis 3 were Diamond Y Spring (-2.875), East Sandia Spring (-0.8437), Caroline Spring (-0.6935) and springs found in the Davis Mountains (-0.3203) and Guadalupe Mountains National Park (-0.8618).

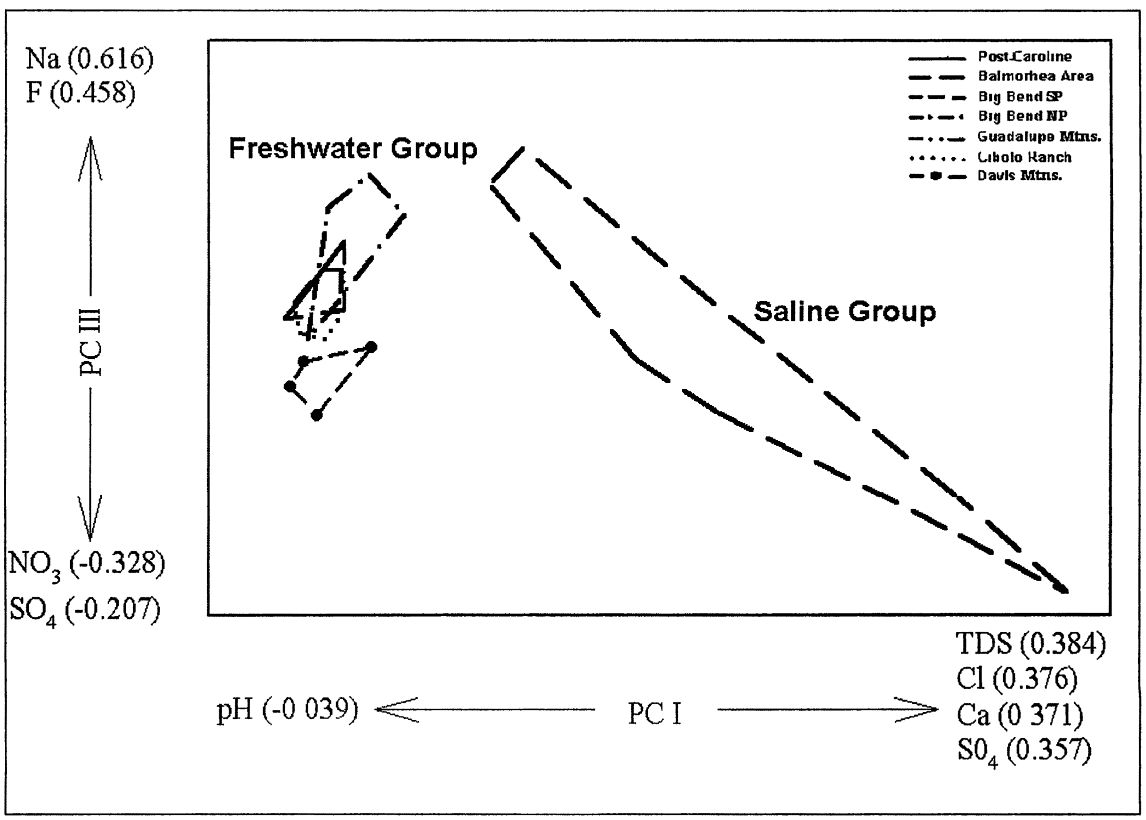

Fig. 10. The First PCA Model. The 1st and 3rd principal components are shown.

The first three PCA axes of the second PCA model, which included only the freshwater group, explained 64% of the total variation in dataset (Table 5). The first PCA axis (35 % of the total variation) described a TDS (0.4347) gradient with SO_4 (0.4068) having the highest positive loadings (Fig. 11). Parameters with negative loadings were NO_3 (-0.0550) and Si (-0.0347). The second PCA axis (18% of the total variation) described High positive loadings for Si (0.4620), F (0.3118), and K (0.3073). The parameters with the highest negative loadings were Mg (-0.4857) and HCO_3 (-0.3347). The third PCA axis (11% of the total variation) described F (0.4157) and pH (0.4731) having the highest positive loadings (Fig. 11). The parameter with the highest negative loading was Cl (-0.5090).

Table 5. Second PCA Model Loadings and % Variance Explained by Parameters.

	PCA		
Parameter	1	2	3
Br	**0.3649**	0 2490	0 0761
Ca	0 3206	-0 2798	0 0219
Cl	0 2963	0 1404	**-0.5090**
F	0 2813	**0.3118**	**0.4157**
HCO_3	0 1813	**-0.3347**	0 2838
K	0 2107	**0.3073**	-0 0184
Mg	0 1783	**-0.4857**	-0 1659
Na	0 3232	0 1202	0.2811
NO_3	**-0.0550**	0 1495	-0 1868
pH	0 1582	-0 2190	**0.4731**
Si	**-0.0347**	**0.4620**	0 0676
SO_4	**0.4068**	-0 0363	-0 2804
TDS	**0.4347**	-0 0302	-0 1806
% Variance Explained	35	18	11

Springs positively associated with PCA axis 1 were Burro Spring (1.318), Mckinney Spring (4.038), Glenn Spring (2.312), Las Cuevas (0.0610), Bone Spring (3.263), Hot Springs #5 (5.871), Hot Springs Rio (4.813) and Post-Caroline (1.914) (Fig.

11). Springs negatively associated with PCA axis 1 were Buttrill Spring (-1.174), Oak Spring (-0.0517), Lava Escondido Spring (-0.4176), Smith House Spring (-0.7365), springs found in Cibolo Ranch (-1.178), the Davis Mountains (-1.871) and Guadalupe Mountains National Park (except for Bone Spring) (-1.051).

Springs positively associated with PCA axis 2 were Caroline Spring (0.6886), Big Bend State Park (1.125), Big Bend National Park (1.088), Cibolo Ranch (1.287) and

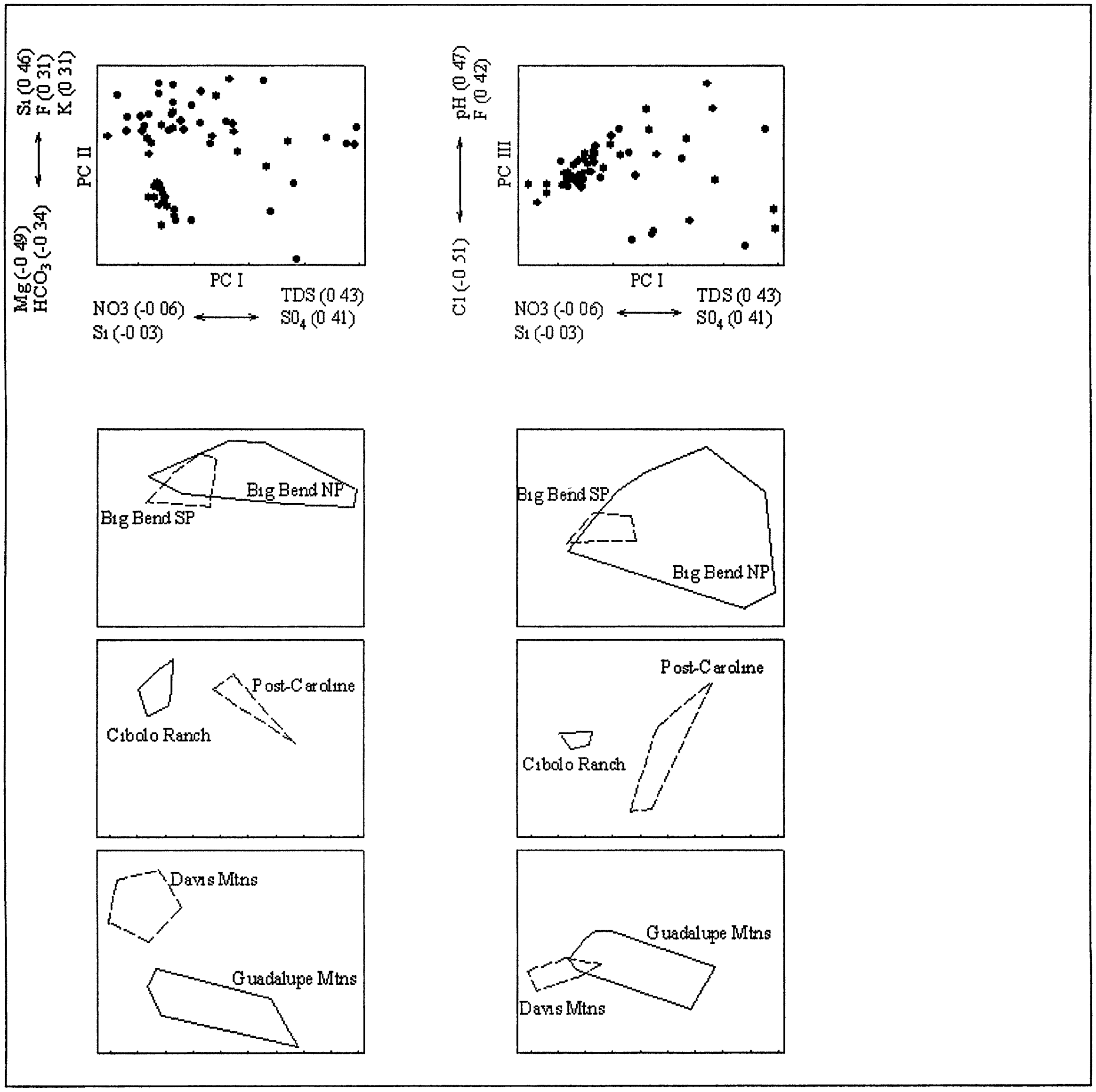

Fig. 11. The Second PCA Model. The first and second principal components are plotted (left). The first and third principal components are plotted (right).

the Davis Mountains (0.9888). Springs negatively associated with PCA axis 2 were Post Spring (-0.6064) and springs found in Guadalupe Mountains National Park (-1.938).

Springs positively associated with PCA axis 3 were Las Cuevas Spring (0.6768), Smith House Spring (0.5418), El Ojo Spring (0.1877), La Morita Spring (0.2283), Mckittrick Spring (0.8096), Guadalupe Spring (0.2553), Post Spring (1.403), Choza Spring (0.0611), Manzanita Spring (0.0109), Smith (0.0126) and springs found in Big Bend National Park (except for Hot Springs #5 and Hot Springs Rio) (1.221). Springs negatively associated with PCA axis 3 were Hot Springs #5 (-1.827), Hot Springs Rio (-2.818), Caroline Spring (-2.423), Upper Pine Spring (-0.1372), Frijole Spring (-0.1212), Bone Spring (-1.122), Cinega Spring (-0.0333), Lava Escondido Spring (-0.2597) and springs found in the Davis Mountains (-0.5202).

Water Quality

Water classifications based on major anions and cations are shown in a Piper trilinear diagram (Fig. 12, the groupings used in this figure coincide with the groupings made in Fig. 8). Water classifications of sampled springs can be broken into several main groups. Post Spring and Caroline Spring along with the springs found in Big Bend National Park, Big Bend State Park, Davis Mountains, Cibolo Ranch and Seven Spring Ranch were all combined into one group, Big Bend-Davis Mountains. This group has a broad concentration range of Ca-HCO_3 dominated water with some samples containing elevated concentrations of SO_4. Cibolo Ranch and Seven Spring Ranch have a tighter concentration range of Ca-HCO_3. Guadalupe National Park has Ca-HCO3 dominated water as well except for one spring, Bone Spring. This spring has elevated levels of SO_4.

The Hot Springs group has Ca-SO_4 dominated water. Most of the Balmorhea area group has Ca-Mg-Na-Cl-SO_4 dominated water. Santa Rosa Spring was included in this group due its similarity in geographic location. However, Santa Rosa Spring has Na-Cl dominated water due to elevated concentrations of Na.

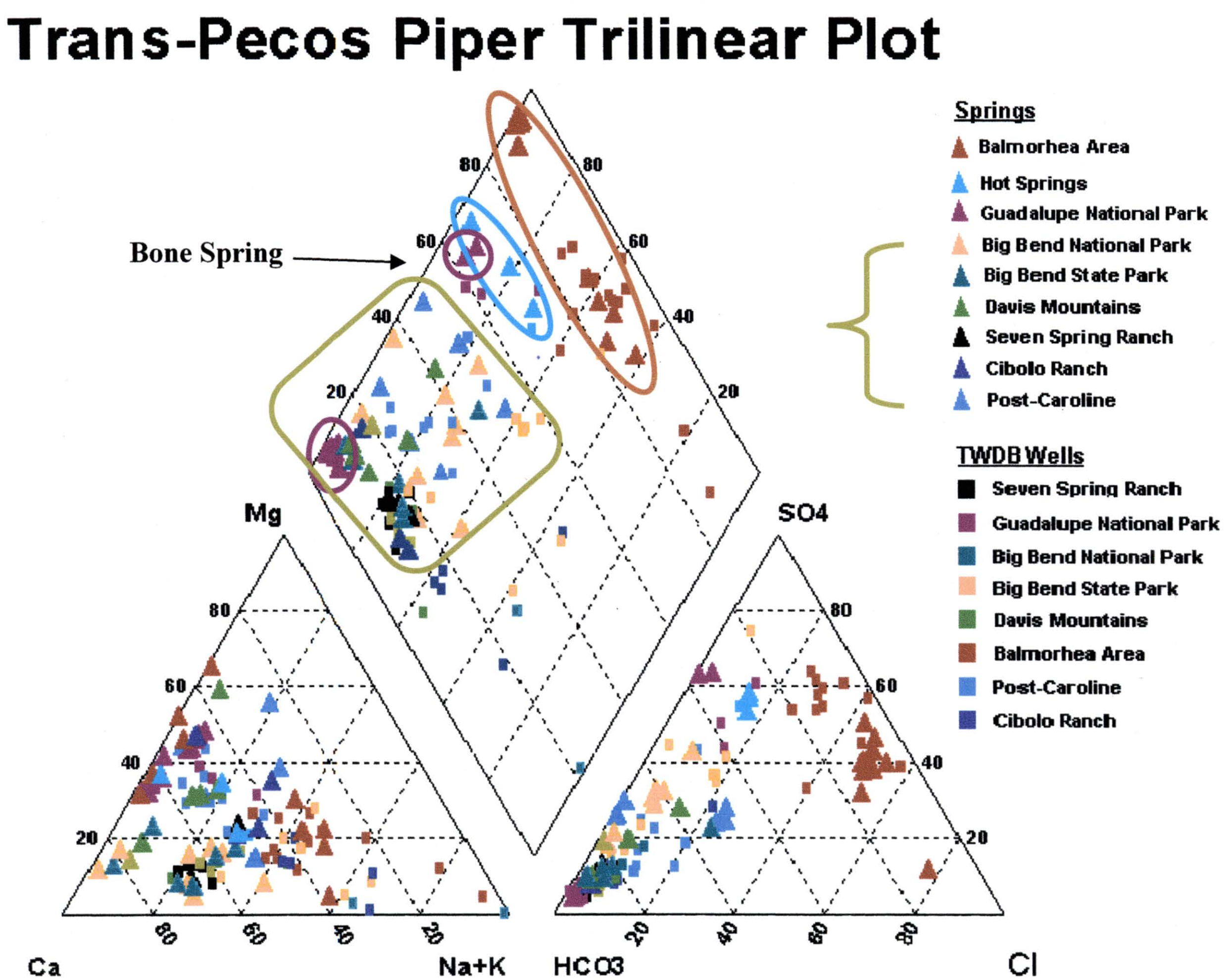

Fig. 12. Piper Trilinear Diagram. Colored groupings correspond to the colors used in the legend. Big Bend-Davis Mts. group shown as a different color.

CHAPTER IV

DISCUSSION

Most of the Trans-Pecos sampled springs have high water quality. Many of the springs have $CaCO_3$ dominated water (Fig. 12), which can be attributed to the interaction of groundwater with limestone. Also, recharge from recent precipitation will contain carbonic acid water because of CO_2 trapped in the water droplets resulting in HCO_3 dominated water. It is important to note that most of the springs with high TDS concentrations are not used as a source for drinking water. High TDS springs are used as a water source for livestock or some type of small irrigation system as well as for aesthetic value.

The first PCA model indicated two distinct groups; springs with saline water and springs with fresh water. The TDS trend described by the first and second PCA axes can be seen in Fig. 9 (Mouser et al. 2005). The Balmorhea Area springs are known to have higher mean TDS, Ca, Cl and SO_4 concentrations (Table 3). The third PCA axis described a gradient within the saline water group that is likely due to high salt contamination to Santa Rosa Spring from a leaking oil cap. The Piper trilinear diagram (Fig. 12) also showed the Balmorhea Area springs separated from the rest of the sampled springs. The gradient within the group can also be seen in Figure 12. Several spring samples have Na-K-Cl dominated water compared to Ca-Mg-SO_4-Cl dominated water. Again this pattern is likely due to Santa Rosa Spring.

The second PCA model showed the Guadalupe National Park springs separated from the rest of the springs (Fig.11). This appears to be caused by higher concentrations of Mg and HCO_3 found in these springs (Appendix 1). The Piper trilinear diagram (Fig. 12) did not show a distinct separation between the Guadalupe Mountains National Park springs and the rest of the sampled springs. However, the Guadalupe Mountains National Park springs appear to very similar and plot very close together on the Piper trilinear diagram. Bone Spring, found on the Western edge of Guadalupe Mountains National Park, has higher SO_4 concentrations. This is likely the cause for the group being stretched across PCA axis 1 (Fig. 11). Figure 12 shows the Bone Spring samples separate from the rest of the Guadalupe Mountains National Park springs due to the higher concentrations of SO_4.

The broad TDS range found in Big Bend National Park group (Fig. 11) is likely due to the two hot springs sampled (Hot Spring Rio and Hot Spring #5). These springs have elevated levels of TDS mainly due to higher $S0_4$ concentrations. This can also be seen in the Piper trilinear diagram (Fig. 12). The hot springs samples are shown separate from the rest of the Big Bend National Park springs because of higher SO_4 concentrations.

The second PCA model (Fig. 11) showed a fairly large amount of overlap between Big Bend National Park (excluding the hot springs), Big Bend State Park, Cibolo Ranch and the Davis Mountains. These springs had similar water quality (Ca-HCO_3) (Fig. 12). The Big Bend-Davis Mountains grouping used in the Piper trilinear diagram fits the PCA model (Fig. 11) as well. However, the PCA model showed variation within the Big Bend-Davis Mountains group due to parameters other than the major anions and cations. The second PCA model showed most of the variation within the Big Bend-Davis Mountains group can be accounted for by Si and F. Concentrations of Si and F are likely influenced by the mineralogy of the various igneous formations with those areas.

Groundwater source classifications were made using major anion and cation concentrations for TWDB wells and sampled springs (Fig. 12). Almost all springs sampled at Guadalupe National Park have similar water quality. The water is dominated by Ca-HCO_3 and is typical of systems influenced by limestone. These springs have considerably lower concentrations of anions and cations and would suggest that these springs are dominated by local recharge (Fig. 12). Guadalupe National Park is part of the Capitan reef Complex aquifer system (CRCX), which is primarily reef limestones. Most of the springs in this area appear to be dominated by limestone dissolution. Bone Spring is the only exception and appears to be influenced by the Bone Spring and Victorio (BSVP) aquifer which is represented by the TWDB well on the east side of the park. Bone Spring has higher concentrations of SO_4 and Mg in the water which is typical of groundwater found in the BSVP system (Ashworth 2001).

San Solomon Spring, Phantom Spring, E. Sandia Spring and Diamond Y Spring have similar water quality. The water is Ca-Mg-Na-Cl-SO_4 dominated and similar in composition to several aquifers, including the Cenozoic Pecos Alluvium (PECS), Lower Cretaceous Series (CRCSL) and Lower Cretaceous Rocks (CPCRL). These springs are fed by several different sources. Diamond Y Springs is likely fed by the Pecos Trough of the Cenozoic Pecos Alluvium. It has moderate to high levels of TDS and higher concentrations of SO_4 in the western portions of the Trough due to interaquifer flow

(Jones 2001). San Salomon, Phantom Spring and E. Sandia Spring have three main groundwater sources; groundwater flowing west out of the Wildhorse Flats, groundwater flowing south from the Rustler Hills and local recharge from the Northeastern edge of the Davis Mountains (Uliana et al. 2006). Flow from the Wildhorse Flats provides most of the groundwater for these springs and the regional flow path is potentially causing the elevated TDS concentrations. Decreases in TDS and increases in discharge and turbidity are due to the local recharge from the Davis Mountains (Uliana and Sharp 2001).

The Davis Mountain springs have Ca-HCO_3 dominated water, which is similar to the volcanic (VLCC) aquifer system. The water quality from these springs is similar to Cinega Spring, El Ojo Spring, La Morita Spring, Head Spring, Headquarter Spring, Boar Spring, Kokernot Spring, Buttril Spring, Mckinney Spring, Oak Spring. It is possible that all these springs are fed by a volcanic aquifer system which is known occur in this region (Ashworth and Hopkins 1995). It is also possible that the volcanic aquifer system extends throughout the area where the springs mentioned above are found. The aquifer system might not be continuous, but similarities in the mineral content of the discontinuous volcanic formations could account for the similarity in water quality. However, the consistent HCO_3 signature in the groundwater is most likely due to the influence of carbonic acid in recent precipitation on groundwater chemistry. The concentration of anions and cations are considerably low compared to the surrounding areas and would suggest that these springs are dominated by local recharge (Fig. 12). This will be discussed later in further detail.

The springs in Big Bend National Park have Ca-HCO_3 dominated water due mainly to limestone deposits in the area. The groundwater source could be from two different aquifers based on the water quality analysis conducted using TWDB well data. The Alluvium and Cretaceous (AVCC) and the Upper Cretaceous aquifer (CRCSU) have Ca-HCO3 water. However, there were few full anion/cation records of TWDB wells to get a sufficient representation of groundwater chemistry. It is possible that the AVCC and CRCSU aquifer systems are minor and overlay parts of the Edward's Trinity. The Edward's Trinity is known to have hydraulic connections to many systems in the area (Anaya 2001).

Caroline Spring, located in Terrell County, has Ca-HCO_3 dominated water. The water chemistry from the TWDB wells match this spring (Fig. 7). The groundwater source for these wells is the Edward's Trinity-Trinity (EDDT) aquifer. It is probable that the EDDT is the groundwater source for this spring (Ashworth and Hopkins 1995).

Post Spring, located in North Brewster County, has Ca-Mg-HCO_3 dominated water and is similar to the Permian (PRMN) aquifer system which is in the vicinity of the spring. All three aquifers are close to Post Spring. Post Spring also has similar water characteristics to Caroline Spring (Table 3) which is likely fed by the Edward's Trinity aquifer. The elevated concentrations in Mg are likely due dissolution of dolomite in the subsurface.

Santa Rosa Spring, located in the Northeast corner of Reeves County, has Na-Cl dominated water and is not similar to any aquifers in the area. Salts from a leaking oil well altered the spring's chemical composition. There are numerous oil wells in this area and sources have documented similar incidents occurring at other locations as well. However, some inferences can be made in regards to the groundwater source of this spring. The Santa Rosa aquifer is located in this region and is likely to be the groundwater source. This aquifer is known to have naturally high occurring TDS concentrations (Price 1989).

Hot Spring Rio and Hot Spring #5 have Ca-SO_4 waters. Both springs are located close to the Rio Grande. These springs are considered to be naturally saline and are distinct from any others sampled. It is likely that water from these springs is influence by mixing with deeper saline groundwater, which is likely the cause for the higher temperatures and the hard water characteristics.

Precipitation in 2004 was above normal (Fig. 13) and in 2005 it returned closer to

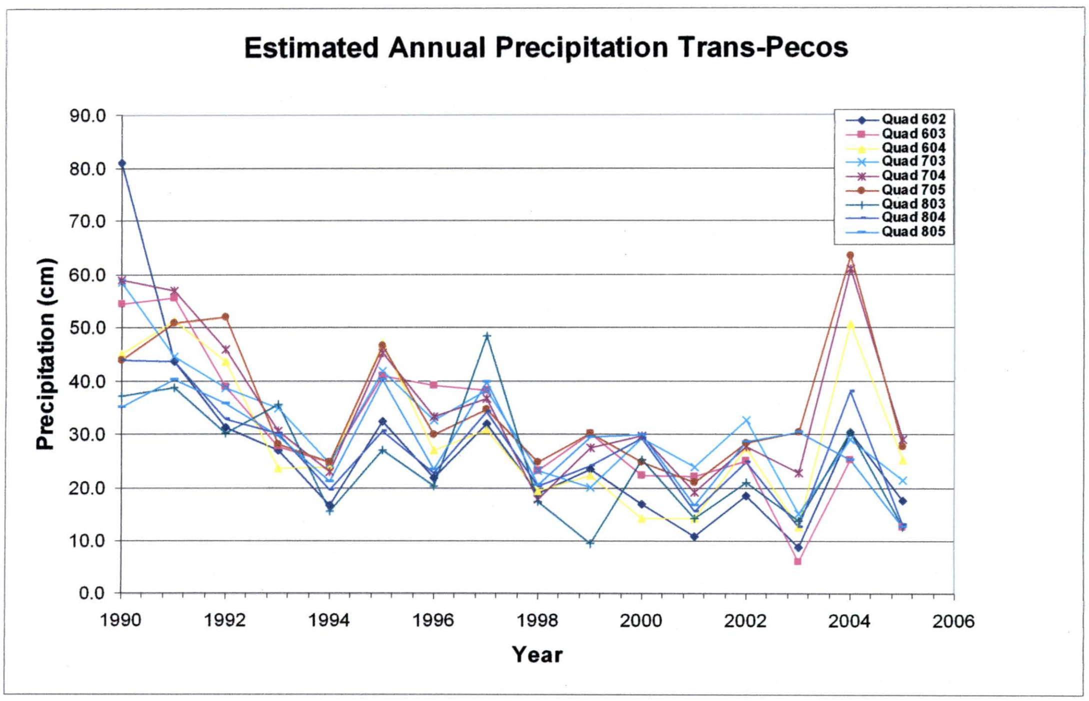

Fig. 13. Estimated Precipitation for the Trans-Pecos Region.

the norm. The increase in rainfall can have several types of impacts. Rainwater can cause high levels of HCO_3 because of high levels of dissolved atmospheric CO_2. Water recharging the areas with greater rainfall will also experience groundwater dilution. This would result in more freshwater in the aquifer systems. The groundwater systems with shorter water retention rates would be influenced more by increased precipitation and sampling soon after precipitation events would also increase variability in water quality.

Areas near the Pecos River with intense irrigation have lowered aquifer levels to the point that the Pecos River recharges the groundwater systems. In areas where irrigation is highest, an increase in precipitation would relieve some of the stress groundwater systems encounter during the growing seasons. The potential recharge from the Pecos River due to high irrigation withdraws would become less of a problem because of increased precipitation. This would cause aquifers in the area to become slightly fresher.

The influence of depth on water quality within aquifer systems reduces the accuracy of predicting aquifer sources. Well depth causes variability because aquifer systems can underlie each other. Groundwater movement between aquifer systems is complex and can cause mixing of chemical properties which are unique to individual systems.

A couple of sampling problems encountered during the study limited the detail of the analysis. Samples were taken as close to the spring discharge as possible, but in several cases a distinct discharge was not found. Water would flow in and out of the alluvial stream bed, making it difficult to determine an exact spring opening. Also the terrain of some springs made it impossible to sample discharge safely. Soil and weather interaction would have significant influences on the water chemistry of springs in which samples were taken from areas other than the spring discharge. The lack of sufficient data from the TWDB on wells in the Trans-Pecos region created gaps in the aquifer classification analysis. Complete records of wells in the study area were rare.

CHAPTER V

CONCLUSIONS

General water classifications and groundwater sources for springs were made with some certainty using major anions and cations. The PCA results gave supporting evidence for the use of major anions and cations as a method to classify groundwater. It would be interesting to substitute one of the cations with Si or F while analyzing the Davis Mountains/Big Bend springs to maximize separation of the springs.

A more extensive look at these Trans-Pecos springs is needed to increase the accuracy of describing the water quality and groundwater sources. The impact of other factors on water quality seems to decrease the accuracy of characterizations and groupings made in this study. Precipitation, chemical interaction, irrigation, well depth, and exact geologic formations are some factors that possibly contribute to the water chemistry differences between wells within a close proximity to each other. There was also sampling problems in the field as well as incomplete well data from TWDB database.

There are already more expensive methods available for groundwater source tracking that reduce uncertainty. A simple and inexpensive method for accurate groundwater source classification is needed for private landowners. One practical application for the results of this study is to begin refining these methods so that in the future an inexpensive groundwater source classification tool will be able. However, this method for groundwater source classification is still unrefined and needs to be studied in more detail to increase accuracy.

APPENDIX

Appendix 1. Major Cation/Anion Results for Sampled Springs (averaged concentrations).

West Texas Spring Major Cation/Anion Results

Sample ID	Ca (mg/l)	Na mg/l)	K (mg/l)	Mg (mg/l)	Cl (mg/l)	SO_4 (mg/l)	HCO_3 (mg/l)	TDS (mg/l)
Caroline Spring	56 4	19 9	4 6	16 0	67 3	90 3	222 0	474 0
Diamond Y Spring	415 0	3 3	16 2	210 0	1573 5	2213 0	300 5	5623.0
Santa Rosa Spring	292 5	533 3	22 9	133 8	1092 0	220.0	250 0	4415 0
Post Spring	42 0	27 1	5 7	34 8	5 0	107 0	356 0	555.3
Kokernot Spring	45 5	3 0	5 1	5 0	5 0	57 0	304 0	536 0
La Morita Spring	27 2	20 8	6 0	11 0	5 0	13 5	173 0	290 5
El Ojo Spring	31 1	9 7	3 9	5 2	5 0	6.7	147.7	231.7
Cinega Spring	30 0	3 1	3 9	18 5	10 0	23.0	208.0	339 0
Lava Escondido Spring	26 6	9 4	8 7	3 8	21 0	29.0	116 0	346 5
Smith House Spring	53 0	2 8	2 5	5 0	5 0	22 0	252 0	351.0
Las Cuevas Spring	47 6	17 1	5 2	5 5	11 0	23 7	251.3	376.7
East Sandia Spring	230 8	3 4	14 0	184 0	1074 5	1149 0	226 0	3342.0
Phantom Spring	113 8	67 0	20 2	65 0	595.5	614 0	207 0	1948 5
San Solomon Spring	114 3	117 6	19 0	29 8	491 3	472 3	208 0	1776.3
Head Spring	23 6	9 0	2 2	2 0	5 0	11 0	108 0	180.0
Headquarter spring	35 7	12 8	8 2	6 4	5 0	16 0	145 5	239 5
Boar Spring	15 0	3 0	3 1	5 5	5 0	15 0	74 0	166 0
Hot Spring #5	88 0	46 9	8 9	30 2	68 0	350 5	212 5	848 5
Glenn Spring	64 4	52 1	6 4	8 2	5 0	72 0	316.0	468 0
Mckinney Spring	106 2	40 3	5 9	9 8	28 5	156 5	273 0	642 0
Oak Spring	55 6	12 7	3 4	4 7	10 7	58 0	149 3	288 3
Burro Spring	43 1	50 8	4 1	1 3	22 0	45 0	146.0	319 0
Buttril Spring	35 5	7 2	4 2	5 5	5 0	37 5	195 0	317 5
Hot Spring (Rio)	82 0	2 3	7 4	31 0	71.0	309 0	220 0	915.0
Manzanita Spring	50 8	2 8	2.1	25 4	5 0	8 0	257.3	264.7
Choza Spring	56 7	3 4	2 3	24 3	5 0	8.3	274.7	280.0
Smith Spring	59 7	2 6	2 2	22 9	5 0	6 7	280 0	291 0
Upper Pine Spring	57 1	3 4	2 2	33 5	5 0	7.3	272 7	285.7
Bone Spring	99 0	17 7	3 7	58.8	10 5	329 0	224.5	747 0
Guadalupe Spring	61 3	6 3	3 1	27.8	5 0	14 5	282 0	298 5
Frijole Spring	45 4	3 8	2 9	18 8	5 0	13 5	254.0	267.0
Mckittrick Spring	55 1	3 6	3 2	25 8	5 0	11 5	262 0	261 0
Limpia Spring	34 8	7 0	1 9	8 9	5 0	16 0	185 0	260.5
Bridge Spring	19 5	5 6	1 3	14 6	5 0	14.0	112 0	194.5
Tobe Spring	11 2	3 6	0 3	4 0	5 0	13 0	34 0	105.0

Appendix 2. Water Chemistry Results for Sampled Springs (averaged concentrations).

West Texas Spring Chemical Results

Sample ID	Total P (mg/l)	Si (mg/l)	NO_3 (mg/l)	F (mg/l)	Br (mg/l)	Fe (mg/l)	Al (mg/l)	As (mg/l)	Cr (mg/l)	Pb (mg/l)	Mn (mg/l)	Se (mg/l)	Ag (mg/l)
Caroline Spring	0 03	14 31	2 10	0 90	0 13	0 04	0 04	0 012	0.05	0.006	0.006	0.014	0.12
Diamond Y Spring	0 03	38 10	6 45	2 20	2 00	0 08	0 05	0 043	0.05	0.043	0 043	0.043	0.05
Santa Rosa Spring	0 03	9 99	1 60	1 80	1 88	0 10	0 01	0 010	0 10	0.002	0.003	0.010	0.25
Post Spring	0 04	14 82	0 20	2 23	0 33	0 07	0 04	0 008	0 03	0.007	0.007	0.013	0.04
Kokernot Spring	0 03	52 80	3 10	1 20	0 03	0 10	0 05	0 010	0 05	0 010	0.098	0.010	0.05
La Morita Spring	0 03	34 66	1 80	1 50	0 11	0 10	0 06	0 051	0 13	0.004	0 004	0 033	0.04
El Ojo Spring	0 03	34 22	0 67	1 23	0 07	0 07	0 04	0 030	0 07	0 006	0 006	0 009	0.12
Cinega Spring	0 21	54 70	1 80	1 70	0 11	0 10	0 05	0 010	0 05	0 010	0 068	0.010	0.05
Lava Escondido Spring	0 03	12 26	0 08	0 55	0 14	0 08	0 05	0 006	0 08	0.004	0 009	0 009	0.04
Smith House Spring	0 03	59 20	0 05	1 00	0 13	0 05	0 05	0 010	0 05	0 010	0 173	0 010	0.05
Las Cuevas Spring	0 03	40 43	0 40	1 97	0 15	0 10	0 04	0 007	0 07	0 006	0.023	0 009	0.12
East Sandia Spring	0 03	32 75	1 25	1 95	0 64	0 08	0 05	0 009	0 05	0 009	0.009	0.009	0.05
Phantom Spring	0 03	17 50	0 60	1 60	0 37	0.10	0 05	0 009	0 05	0.009	0.009	0 009	0.05
San Solomon Spring	0 03	17 93	1 07	1 43	0 33	0 07	0 04	0 014	0.07	0.006	0.006	0 019	0.12
Head Spring	0 03	2 39	1 50	0 50	0 05	0 10	0 02	0 002	0 10	0 001	0.001	0 010	0.25
Headquarter Spring	0 03	28 64	1 65	0 65	0 11	0 08	0 04	0 014	0 08	0.004	0 005	0.016	0.15
Boar Spring	0 11	46 00	1 60	0 20	0 07	0 30	0 05	0 010	0 05	0.010	0.133	0.010	0.05
Hot Spring #5	0 01	15 38	0 40	2 00	0 30	0 05	0 03	0 006	0 03	0 006	0.006	0 004	0 03
Glenn Spring	0 07	25 60	0 05	3 95	0 14	0 16	0 03	0 006	0 03	0 006	0 006	0.009	0.01
Mckinney Spring	0 03	41 35	0 45	3 75	0 31	0 16	0 03	0 006	0 03	0 006	0.080	0.009	0.03
Oak Spring	0 03	23 98	0 50	3 43	0 09	0 12	0 04	0 008	0 04	0 007	0 007	0 009	0.04
Burro Spring	0 03	22 65	3 20	4 10	0 22	0 00	0 01	0 005	0 00	0 004	0 004	0.020	0.00
Buttril Spring	0 03	58 65	0 40	0 95	0 09	0 08	0 05	0 009	0 05	0.009	0.009	0.009	0.05
Hot Spring (Rio)	0 03	24 80	0 30	2 00	0 30	0 10	0 05	0 010	0 05	0 010	0.010	0.010	0.05
Manzanita Spring	0 03	4 50	0 25	0 13	0 03	0 04	0 04	0 008	0 04	0 008	0.008	0.010	0.04
Choza Spring	0 03	6 30	0 77	0 13	0 03	0 07	0 04	0 008	0 05	0 008	0.008	0.010	0.04
Smith Spring	0 03	4 50	0 73	0 10	0 03	0 05	0 04	0 008	0 05	0.008	0.008	0.010	0.04
Upper Pine Spring	0 03	6 14	1 07	0 10	0 03	0 07	0 04	0 008	0 04	0 008	0 008	0 010	0 04
Bone Spring	0 03	9 68	0 20	0 85	0 08	0 18	0 03	0 008	0 05	0 007	0 014	0 010	0.03
Guadalupe Spring	0 04	7 75	0 65	0 25	0 04	0 90	0 43	0 008	0 05	0 007	0 085	0 010	0.03
Frijole Spring	0 03	5 13	1 10	0 15	0 03	0 03	0 03	0 008	0 05	0 007	0 007	0 010	0.03
Mckittrick Spring	0 03	4 73	0 65	0 15	0 03	0 03	0 03	0 008	0 05	0 007	0.007	0.010	0.03
Limpia Spring	0 08	30 85	0 05	0 60	0 07	0 08	0 05	0 009	0 05	0 009	0 024	0 009	0.05
Bridge Spring	0 23	42 15	0 05	0 40	0 11	0 08	0 05	0 009	0 05	0.009	0 066	0 009	0.05
Tobe Spring	0 00	14.60	0 05	0 10	0 00	0 20	0 05	0 008	0 05	0 008	0.008	0.008	0.05

Appendix 3. Results for Physical Parameters Taken at Each Spring.

West Texas Springs Physical Data

Sample ID	pH	Specific Conductance (µs/cm)	Water Temperature (°C)
Caroline Spring	6 15	833 0	21 93
Diamond Y Spring	6 54	7880 5	19 90
Santa Rosa Spring	6 18	6350 0	25 71
Post Spring	7 23	993 3	15 96
Kokernot Spring	6 68	889 0	20 29
La Morita Spring	6 69	426 5	24 52
El Ojo Spring	6 57	215 0	22 85
Cinega Spring	6 72	482 0	23 49
Lava Escondido Spring	7 12	356 5	18 63
Smith House Spring	6 55	549 0	21 63
Las Cuevas Spring	6 38	590 7	22 54
East Sandia Spring	6 25	5387 0	19 60
Phantom Spring	7 01	3307 5	25 10
San Solomon Spring	6 54	2892 7	24 44
Head Spring	6 09	228 0	20 54
Headquarter Spring	6 34	367 0	20.78
Boar Spring	5 93	219 0	20 87
Hot Spring #5	6 98	1292 5	35 19
Glenn Spring	7 42	793 0	22 10
Mckinney Spring	6 86	973 5	19 25
Oak Spring	6 99	438 7	18 15
Burro Spring	7 70	477 0	23 55
Buttril Spring	6 23	499 5	19 23
Hot Spring (Rio)	6 53	1380 0	40 40
Manzanita Spring	6 79	496 3	15 17
Choza Spring	6 92	537 3	17 22
Smith Spring	6 83	542 0	14 86
Upper Pine Spring	6 92	556 3	15 10
Bone Spring	7 36	476 8	14 89
Guadalupe Spring	7 06	3012 0	13 64
Frijole Spring	6 82	501 0	16 47
Mckittrick Spring	7 95	499 5	15 60
Limpia Spring	6 13	417 0	12 06
Bridge Spring	9 32	277 0	5 10
Tobe Spring	6 66	109 0	5 20

Appendix 4. West Texas Dataset. Elevation was estimated from a USGS topo map.

Sample ID	Date	Elevation	Air Temp. (°C)	pH	Specific Conductance (μs)	Water Temp (oC)	Total Alkalinity (mg/L)	TDS (mg/L)	Si (mg/L)	Cl (mg/L)	SO4 (mg/L)	N03 (mg/L)	F (mg/L)	Br (mg/L)
Caroline Spring	8/12/04	2054		5 77	781	22 01	218	534	3 92	67	102	2 00	1 00	0 12
Caroline Spring	3/11/05			6 47	892	21 82	225	478	17 90	72	88	1 80	0 90	0 14
Caroline Spring	5/13/05		33	6 21	826	21 96	223	410	21 10	63	81	2 50	0 80	0 12
Diamond Y Spring	1/15/04	2793	17	6 68	8072	18 58	304	5685	32 60	1509	2305	6 40	2 40	
Diamond Y Spring	5/19/05		32	6 39	7689	21 22	297	5561	43 60	1638	2121	6 50	2 00	2 00
Santa Rosa Spring	8/10/04	2436	30	6 18	6350	25 71	250	4415	9 99	1092	220	1 60	1 80	1 88
Post Spring	10/10/04	3890	28	7 91	984	15 78	366	581	7 96	<10	124	0 20	2 50	0 34
Post Spring	3/11/05			7 23	1021	10 92	352	557	16 80	<10	97	0 30	2 20	0 33
Post Spring	5/13/05		29	6 56	975	21 18	350	528	19 70	<10	100	0 10	2 00	0 32
Kokernot Spring	5/16/05	4383	25	6 68	889	20 29	304	536	52 80	<10	57	3 10	1 20	< 05
La Morita Spring	8/11/04	4087		6 21	401	24 72	174	275	10 23	<10	14	1 80	1 50	0 11
La Morita Spring	3/13/05			7 16	452	24 32	172	306	59 10	<10	13	1 80	1 50	0 10
El Ojo Spring	8/11/04	4279		6 06	249	24 06	147	254	2 76	<10	<10	0 60	1 30	0 07
El Ojo Spring	3/13/05			6 82	365	22 15	148	216	47 40	<10	10	0 90	1 30	0 08
El Ojo Spring	5/16/05		18	6 82	31	22 35	148	225	52 50	<10	<10	0 50	1 10	0 07
Cinega Spring	5/16/05	4040	24	6 72	482	23 49	208	339	54 70	10	23	1 80	1 70	0 11
Lava Escondido Spring	8/11/04	4241		6 82	197	24 86	92	387	4 12	<10	11	0 10	0 40	< 05
Lava Escondido Spring	3/13/05			7 41	516	12 4	140	306	20 40	37	47	< 1	0 70	0 26

Appendix 4. Continued.

Sample ID	Date	Elevation	Air Temp. (°C)	pH	Specific Conductance (μs)	Water Temp. (oC)	Total Alkalinity (mg/L)	TDS (mg/L)	Si (mg/L)	Cl (mg/L)	SO4 (mg/L)	N03 (mg/L)	F (mg/L)	Br (mg/L)
Smith House Spring	5/15/05	4141	22	6 55	549	21 63	252	351	59 20	<10	22	< 1	1 00	0 13
Las Cuevas Spring	8/11/04	4209		6 35	566	23 36	256	382	12 20	10	29	0 80	1 90	0 13
Las Cuevas Spring	3/13/05			6 35	627	21 81	244	385	51 80	12	21	0 30	2 10	0 16
Las Cuevas Spring	5/15/05		21	6 45	579	22 44	254	363	57 30	<10	21	0 10	1 90	0 16
East Sandia Spring	1/15/05	3135	10	5 95	5205	17 04	240	3156	36 80	988	1156	1 40	2 00	0 64
East Sandia Spring	5/17/05		35	6 55	5569	22 15	212	3528	28 70	1161	1142	1 10	1 90	0 64
Phantom Spring	3/14/05	3471		7 12	2990	24 04	196	1658	18 30	491	544	1 00	1 50	0 35
Phantom Spring	5/17/05		34	6 89	3625	26 15	218	2239	16 70	700	684	0 20	1 70	0 39
San Salomon Spring	8/11/04	3313	19	5 97	2238	24 13	188	1465	9 38	377	309	1 80	1 20	0 27
San Salomon Spring	3/14/05			7 01	3155	24 19	216	1826	22 90	521	528	1 00	1 60	0 37
San Salomon Spring	5/17/05		31	6 64	3285	25	220	2038	21 50	576	580	0 40	1 50	0 36
Head Spring	8/11/04	4663		6 09	228	20 54	108	180	2 39	<10	11	1 50	0 50	0 05
Headquarter Spring	8/11/04	3783		6 01	350	22 26	152	257	9 78	<10	15	1 50	0 70	0 10
Headquarter Spring	3/14/05			6 67	384	19 29	139	222	47 50	<10	17	1 80	0 60	0 11
Boar Spring	5/16/05	4369	31	5 93	219	20 87	74	166	46 00	<10	15	1 60	0 20	0 07
Hot Spring #5	10/8/04	1842		6.93	1206	35 29	209	812	8 16	67	336	0 40	2 00	0 28
Hot Spring #5	3/11/05			7 02	1379	35 08	216	885	22 60	69	365	0 40	2 00	0 31

Appendix 4. Continued.

Sample ID	Date	Elevation	Air Temp. (°C)	pH	Specific Conductance (µs)	Water Temp. (oC)	Total Alkalinity (mg/L)	TDS (mg/L)	Si (mg/L)	Cl (mg/L)	SO4 (mg/L)	N03 (mg/L)	F (mg/L)	Br (mg/L)
Glenn Spring	10/8/04	2726		7 27	831	25 67	332	528	18 59	<10	94	< 1	4 40	0 15
Glenn Spring	3/12/05			7 56	755	18 53	300	408	32 60	<10	50	< 1	3 50	0 13
Mckinney Spring	10/8/04	2832		7 31	1021	24 28	278	693	25 10	33	197	0 20	3 90	0 34
Mckinney Spring	3/11/05			6 4	926	14 22	268	591	57 60	24	116	0 70	3 60	0 27
Oak Spring	10/9/04	2567		7 3	450	19 49	148	287	12 84	10	63	0 60	4 00	0 10
Oak Spring	3/11/05			7 63	474	17 03	150	274	26 10	12	54	0 70	3 30	0 09
Oak Spring	5/15/05		21	6 05	392	17 92	150	304	33 00	10	57	0 20	3 00	0 09
Burro Spring	10/9/04	3293	24	7 7	477	23 55	146	319	22 65	22	45	3 20	4 10	0 22
Buttrill Spring	3/11/05	3239		6 9	520	17 25	192	299	58 40	<10	43	0 50	1 00	0 09
Buttrill Spring	5/14/05		24	5 55	479	21 21	198	336	58 90	<10	32	0 30	0 90	0 09
Hot Spring (rio)	5/14/05	1845	34	6 53	1380	40 4	220	915	24 80	71	309	0 30	2 00	0 30
Manzanita Spring	10/15/04	5529	29	6 41	474	17 6	260	259	3 91	<10	14	0 50	0 20	< 05
Manzanita Spring	4/16/05		13	7 31	540	6 82	266	261	3 80	<10	<10	0 20	0 10	< 05
Manzanita Spring	5/18/05		27	6 66	475	21 1	246	274	5 80	<10	<10	< 1	0 10	< 05
Choza Spring	10/15/04	5279	26	7 78	491	17 85	270	280	4 41	<10	10	0 90	0 20	< 05
Choza Spring	4/16/05		12	6 55	570	16 54	278	256	6 90	<10	5	0 80	0 10	< 05
Choza Spring	5/18/05		28	6 42	551	17 26	276	304	7 60	<10	10	0 60	0 10	< 05

Appendix 4. Continued.

Sample ID	Date	Elevation	Air Temp. (°C)	pH	Specific Conductance (μs)	Water Temp. (oC)	Total Alkalinity (mg/L)	TDS (mg/L)	Si (mg/L)	Cl (mg/L)	SO4 (mg/L)	N03 (mg/L)	F (mg/L)	Br (mg/L)
Smith Spring	10/15/04	5981	25	7 31	475	14 75	276	304	2 89	<10	10	1 10	0 10	< 05
Smith Spring	4/16/05		18	6 69	592	14 83	278	266	5 00	<10	<10	0 70	0 10	< 05
Smith Spring	5/18/05		25	6 5	559	14 99	286	303	5 60	<10	<10	0 40	0 10	0 03
Upper Pine Spring	10/15/04	6029	29	7 6	570	14 81	266	307	4 43	<10	12	1 50	0 10	< 05
Upper Pine Spring	4/16/05		15	6 7	567	14 94	276	291	6 70	<10	<10	1 10	0 10	0 03
Upper Pine Spring	5/18/05		27	6 47	532	15 55	276	259	7 30	<10	<10	0 60	0 10	0 03
Bone Spring	10/16/04	5418	25	8 15	942	14 4	225	743	7 75	<10	312	0 30	0 90	0 08
Bone Spring	4/16/05		21	6 56	11 59	15 37	224	751	11 60	16	346	0 10	0 80	0 07
Guadalupe Spring	10/16/04	5378	13	7 88	494	13 25	300	320	7 19	<10	18	0 50	0 30	0 06
Guadalupe Spring	4/16/05		12	6 24	5530	14 03	264	277	8 30	<10	11	0 80	0 20	0 03
Frijole Spring	10/16/04	5506	24	7 33	449	16 52	246	266	2 76	<10	17	1 40	0 20	< 05
Frijole Spring	4/16/05		16	6 3	553	16 42	262	268	7 50	<10	10	0 80	0 10	0 03
Mckittrick Spring	10/16/04	5086	27	8 15	474	17 4	268	270	3 95	<10	12	0 80	0 20	< 05
Mckittrick Spring	4/16/05		12	7 74	525	13 8	256	252	5 50	<10	11	0 50	0 10	0 03
Limpia Spring	1/14/05	6326	9	6	415	6 87	188	268	18 60	<10	17	< 1	0 60	0 06
Limpia Spring	5/17/05		28	6 26	419	17 25	182	253	43 10	<10	15	< 1	0 60	0 08
Bridge Spring	1/14/05	6946	16	6 12	239	4 3	82	153	38 00	<10	17	< 1	0 40	
Bridge Spring	5/19/05		19	12 52	315	5 9	142	236	46 30	<10	11	< 1	0 40	0 11
Tobe Spring	1/14/05	7295	8	6 66	109	5 2	34	105	14 60	<10	13	< 1	0 10	< 05

Appendix 4. Continued.

Sample ID	Date	Total Hardness (mg/L)	Total P (mg/L)	Ca (mg/L)	Na (mg/L)	K (mg/L)	Mg (mg/L)	Fe (mg/L)	Al (mg/L)	As (mg/L)	Cr (mg/L)	Pb (mg/L)	Mn (mg/L)	Se (mg/L)	Ag (mg/L)	Anions	Cations
Caroline Spring	8/12/04	159	< 05	49 20	39 90	3 60	8 89	< 02	< 017	0 017	0 100	< 001	< 001	0 024	< 5	7 74	4 93
Caroline Spring	3/11/05	216	< 05	54 50	17 70	5 50	19 50	< 1	< 1	< 015	< 1	< 015	< 015	< 015	< 1	7 70	5 10
Caroline Spring	5/13/05	243	< 05	65 50	2 20	4 60	19 60	< 1	< 1	< 02	< 1	< 02	< 02	< 02	< 1	5 64	5 15
Diamond Y Spring	1/15/04	2516	< 05	480 00	3 60	15 00	320 00	< 1	< 1	< 015	<	< 015	< 015	< 015	< 1	95 81	50 44
Diamond Y Spring	5/19/05	1286	< 05	350 00	3 00	17 40	100 00	0 100	< 1	< 02	< 1	< 02	< 02	< 02	< 1	95 50	25 83
Santa Rosa Spring	8/10/04	1281	< 05	292 50	533 30	22 90	133 75	< 2	< 017	< 004	0 100	0 002	0 003	< 02	< 5	39 65	48 81
Post Spring	10/10/04	265	< 05	51 50	54 20	4 13	38 30	< 007	< 017	< 01	< 007	< 007	< 007	0 021	0 009	8 08	8 92
Post Spring	3/11/05	263	< 05	33 00	24 80	7 50	44 00	0 100	< 1	< 015	< 01	< 015	< 015	< 015	< 01	8 13	6 35
Post Spring	5/13/05	194	0 06	41 50	2 20	5 50	22 00	0 100	< 1	< 02	< 1	< 02	< 02	< 02	< 1	8 15	3 98
Kokernot Spring	5/16/05	134	< 05	45 50	3 00	5 10	5 00	0 100	< 01	< 02	< 01	< 02	0 098	< 02	< 01	6 53	2 82
La Morita Spring	8/11/04	135	< 05	35 80	29 10	2 50	11 03	< 2	< 017	0 026	0 200	< 001	< 001	0 059	< 5	3 41	3 36
La Morita Spring	3/13/05	91	< 05	18 50	12 40	9 50	11 00	0 100	< 1	< 015	< 1	< 015	< 015	< 015	< 1	3 35	2 37
El Ojo Spring	8/11/04	124	< 05	42 20	15 30	1 40	4 53	< 2	0 022	0 006	0 100	< 001	< 001	< 020	< 5	2 75	3 15
El Ojo Spring	3/13/05	83	< 05	23 50	10 80	8 50	6 00	< 1	< 1	< 015	< 1	< 015	< 015	< 015	< 1	2 87	2 14
El Ojo Spring	5/16/05	89	< 05	27 50	2 90	1 80	5 00	< 1	< 1	< 02	< 01	< 02	< 02	< 02	< 1	2 76	1 91
Cinega Spring	5/16/05	151	0 21	30 00	3 10	3 90	18 50	0 100	< 1	< 02	< 1	< 02	0 068	< 02	< 1	4 32	3 16
Lava Escondido Spring	8/11/04	65	< 05	23 20	5 70	4 80	1 61	< 2	0 041	0 004	0 100	< 001	0 010	< 02	< 5	1 93	1 54
Lava Escondido Spring	3/13/05	97	< 05	30 00	13 00	12 50	6 00	< 1	< 1	< 015	< 1	< 015	< 015	< 015	< 1	4 39	2 56

Appendix 4. Continued.

Sample ID	Date	Total Hardness (mg/L)	Total P (mg/L)	Ca (mg/L)	Na (mg/L)	K (mg/L)	Mg (mg/L)	Fe (mg/L)	Al (mg/L)	As (mg/L)	Cr (mg/L)	Pb (mg/L)	Mn (mg/L)	Se (mg/L)	Ag (mg/L)	Anions	Cations
Smith House Spring	5/15/05	153	< 05	53 00	2 80	2 50	5 00	< 1	< 1	< 02	< 1	< 02	0 173	< 02	< 1	4 87	3 49
Las Cuevas Spring	8/11/04	216	< 05	77 90	33 00	3 90	5 13	< 2	0 018	< 004	0 100	< 001	0 052	< 020	< 5	5 23	5 75
Las Cuevas Spring	3/13/05	119	< 05	38 00	15 60	9 00	6 00	0 100	< 1	< 015	< 1	< 015	< 015	< 015	< 1	4 91	3 07
Las Cuevas Spring	5/15/05	90	0 05	27 00	2 70	2 60	5 50	0 100	< 1	< 02	< 1	< 02	< 02	< 02	< 1	4 88	1 92
East Sandia Spring	1/15/05	1789	< 05	241 60	3 80	16 00	288 00	< 1	< 1	< 015	< 1	< 015	< 015	< 015	< 1	56 03	34 28
East Sandia Spring	5/17/05	879	< 05	220 00	2 90	12 00	80 00	0 100	< 1	< 02	< 1	< 02	< 02	< 02	< 1	60 14	17 69
Phantom Spring	3/14/05	509	< 05	105 00	131 00	20 50	60 00	0 100	< 1	< 015	< 1	< 015	< 015	< 015	< 1	28 51	15 88
Phantom Spring	5/17/05	594	< 05	122 50	2 90	19 80	70 00	0 100	< 1	< 02	< 1	< 02	< 02	< 02	< 1	37 68	12 01
San Salomon Spring	8/11/04	68	< 05	124 30	217 90	16 00	42 50	< 2	0 028	0 023	0 100	< 001	< 001	0 039	< 5	20 28	19 18
San Salomon Spring	3/14/05	409	< 05	101 00	132 00	21 00	38 00	< 1	< 1	< 015	< 1	< 015	< 015	< 015	< 1	29 36	13 91
San Salomon Spring	5/17/05	330	< 05	117 50	2 90	20 00	9 00	0 050	< 1	< 02	< 1	< 02	< 02	< 02	< 1	32 06	6 74
Head Spring	8/11/04	67	< 05	23 60	9 00	2 20	2 00	< 2	0 023	< 004	0 100	< 001	< 001	< 020	< 5	2 22	1 74
Headquarter Spring	8/11/04	145	< 05	48 40	16 00	5 80	5 97	< 2	0 032	0 020	0 100	< 001	0 002	0 024	< 5	3 05	3 61
Headquarter Spring	3/14/05	85	< 05	23 00	9 60	10 50	6 80	0 100	< 1	< 015	< 1	< 015	< 015	< 015	< 1	2 88	2 13
Boar Spring	5/16/05	60	0 11	15 00	3 00	3 10	5 50	0 300	< 1	< 02	< 1	< 02	0 133	< 02	< 01	1 74	1 35
Hot Spring #5	10/8/04	353	< 005	98 90	63 80	6 26	25 80	< 007	< 017	< 01	< 007	< 007	< 007	< 02	< 009	9 83	12 43
Hot Spring #5	3/11/05	334	< 05	77 00	30 00	11 50	34 50	0 100	< 1	< 015	< 1	< 015	< 015	< 015	< 1	13 21	7 92

Appendix 4. Continued.

Sample ID	Date	Total Hardness (mg/L)	Total P (mg/L)	Ca (mg/L)	Na (mg/L)	K (mg/L)	Mg (mg/L)	Fe (mg/L)	Al (mg/L)	As (mg/L)	Cr (mg/L)	Pb (mg/L)	Mn (mg/L)	Se (mg/L)	Ag (mg/L)	Anions	Cations
Glenn Sprıng	10/8/04	256	0 08	88 70	82 20	4 20	8 40	0 028	< 017	< 01	< 007	< 007	< 007	< 020	< 009	8 70	7 72
Glenn Spring	3/12/05	132	0 05	40 00	22 00	8 50	8 00	0 300	< 1	< 015	< 1	< 015	0 017	< 015	< 1	6 26	3 63
Mckinney Spring	10/8/04	423	< 05	151 80	62 20	3 24	10 60	0 028	< 017	< 01	< 007	< 007	< 007	< 020	< 009	11 16	9 74
Mckinney Spring	3/11/05	188	< 05	60 50	18 40	8 50	9 00	0 300	< 1	< 015	< 1	< 015	0 082	< 015	< 01	7 64	4 58
Oak Spring	10/9/04	140	< 05	52 80	23 30	2 19	2 10	0 130	< 017	< 01	< 007	< 007	< 007	< 020	< 009	3 83	4 11
Oak Spring	3/11/05	92	< 05	28 50	12 40	7 00	5 00	0 100	< 1	< 015	< 1	< 015	< 015	< 015	< 1	5 23	5 75
Oak Spring	5/15/05	242	< 05	85 50	2 40	1 10	7 00	< 1	< 1	< 02	< 1	< 02	< 02	< 02	< 1	4 01	4 95
Burro Spring	10/9/04	113	< 05	43 10	50 80	4 11	1 30	< 007	< 017	< 01	< 007	< 007	< 007	0 020	< 009	4 47	4 08
Buttrill Spring	3/11/05	107	< 05	33 00	12 00	7 50	6 00	0 100	< 1	< 015	< 1	< 015	< 015	< 015	< 1	4 30	2 67
Buttrill Sprıng	5/14/05	115	< 05	38 00	2 30	0 80	5 00	< 1	< 1	< 02	<1	< 02	< 02	< 02	< 1	4 17	2 41
Hot Spring (Rio)	5/14/05	332	< 05	82 00	2 30	7 40	31 00	0 100	< 1	< 020	< 1	< 020	< 020	< 020	< 1	12 17	6 75
Manzanita Spring	10/15/04	286	< 05	69 90	2 80	2 21	26 70	0 029	< 017	< 01	< 007	< 007	< 007	< 02	0 011	5 81	4 84
Manzanita Spring	4/16/05	220	< 05	43 50	4 00	3 80	27 00	< 1	< 1	< 02	0 100	< 02	< 02	< 02	< 1	4 75	4 57
Manzanita Spring	5/18/05	190	< 05	39 00	1 60	0 40	22 50	0 100	< 1	< 02	< 1	< 02	< 02	< 02	< 1	4 41	3 87
Choza Spring	10/15/04	304	< 05	75 00	2 60	2 05	25 50	< 007	< 017	< 01	< 007	< 007	< 007	< 02	< 009	5 95	4 94
Choza Spring	4/16/05	214	< 05	44 50	5 20	4 20	25 00	0 100	< 1	< 02	0 100	< 02	< 02	< 02	< 1	4 97	4 51
Choza Spring	5/18/05	218	< 05	50 50	2 30	0 60	22 50	0 100	< 1	< 02	< 1	< 02	< 02	< 02	< 1	5 03	4 48

Appendix 4. Continued.

Sample ID	Date	Total Hardness (mg/L)	Total P (mg/L)	Ca (mg/L)	Na (mg/L)	K (mg/L)	Mg (mg/L)	Fe (mg/L)	Al (mg/L)	As (mg/L)	Cr (mg/L)	Pb (mg/L)	Mn (mg/L)	Se (mg/L)	Ag (mg/L)	Anions	Cations
Smith Spring	10/15/04	308	< 05	68 20	1 60	1 91	20 10	< 007	< 017	< 01	< 007	< 007	< 007	< 02	<009	5 13	5 04
Smith Spring	4/16/05	231	< 05	49 50	4 60	4 20	26 00	< 1	< 1	<02	0 100	< 02	< 02	< 02	< 1	4 96	4 81
Smith Spring	5/18/05	246	< 05	61 50	1 50	0 50	22 50	0 100	< 1	< 02	< 1	< 02	< 02	< 02	< 1	5 10	4 99
Upper Pine Spring	10/15/04	279	< 05	75 70	3 30	2 23	25 00	0 056	< 017	<001	< 007	< 007	< 007	< 020	< 009	5 98	4 92
Upper Pine Spring	4/16/05	217	< 05	45 00	4 80	3 80	25 50	< 1	< 1	< 02	< 1	< 02	< 02	< 02	< 1	4 94	4 56
Upper Pine Spring	5/18/05	332	< 05	50 50	2 20	0 60	50 00	0 100	< 1	< 02	< 1	< 02	< 02	< 02	< 1	4 42	6 74
Bone Spring	10/16/04	578	< 05	122 00	20 30	3 30	66 30	0 167	< 017	< 01	< 007	< 007	0 017	< 020	< 009	12 44	10 45
Bone Spring	4/16/05	401	< 05	76 00	15 10	4 00	51 20	0 200	< 1	< 02	0 100	< 02	< 02	< 02	< 1	11 45	8 67
Guadalupe Spring	10/16/04	336	0 05	77 60	6 50	2 48	28 50	1 605	0 808	< 01	< 007	< 007	0 149	< 020	0 011	6 59	5 61
Guadalupe Spring	4/16/05	224	< 05	45 00	6 00	3 80	27 00	0 200	< 1	< 02	0 100	< 02	0 021	< 02	< 1	4 85	4 74
Frijole Spring	10/16/04	274	< 05	45 20	2 10	1 83	13 50	< 007	< 017	< 01	< 007	< 007	< 007	< 02	< 009	3 46	4 68
Frijole Spring	4/16/05	212	< 05	45 50	5 40	4 00	24 00	< 1	< 1	< 02	0 100	< 02	< 02	< 02	< 1	4 80	4 48
Mckittrick Spring	10/16/04	298	< 05	70 60	2 40	2 09	26 60	< 007	< 017	< 01	< 007	< 007	< 007	< 02	< 009	5 82	4 94
Mckittrick Spring	4/16/05	202	< 05	39 50	4 80	4 20	25 00	< 1	< 1	< 02	0 100	< 02	< 02	< 02	< 1	4 71	4 24
Limpia Spring	1/14/05	147	0 07	37 60	10 70	1 20	12 80	< 1	< 1	< 015	< 1	< 015	< 015	< 015	< 1	3 68	3 40
Limpia Spring	5/17/05	100	0 08	32 00	3 20	2 50	5 00	0 100	< 1	< 02	< 1	< 02	0 041	< 02	< 1	3 54	2 15
Bridge Spring	1/14/05	75	0 12	18 00	7 70	0 50	7 40	< 1	< 1	< 015	< 1	< 015	0 042	< 015	< 1	1 89	1 85
Bridge Spring	5/19/05	142	0 33	21 00	3 50	2 00	21 80	0 100	< 1	< 02	< 1	< 02	0 090	< 02	< 1	2 79	3 00
Tobe Spring	1/14/05	44	< 05	11 20	3 60	0 30	4 00	0 200	< 1	< 015	< 1	< 015	< 015	< 015	< 1	0 99	1 06

REFERENCES

Anaya, R. 2001. *An overview of theEdward's-Trinity aquifer system, Central-West Texas*. Ch. 8, *Aquifers of West Texas*. Texas: Texas Water Development Board. TWDB, Report 356.

Aquachem 4.0. 2003. Waterloo Hydrogeologic Inc: Ontario.

Arcview Gis 3.3. 2002. Environmental Research Institute, Inc.

Ashworth, J. B. 1995. *Ground-water resources of the Bone Spring-Victorio Peak Aquifer in the Del Valley area, Texas.* Texas: Texas Water Development Board. TWDB, Report 344.

Ashworth, J. B. 1990. *Evaluation of ground-water resources in parts of Loving, Pecos, Reeeves, Ward, and Winkler Counties, Texas.* Texas: Texas Water Development Board. TWDB, Report 317.

Ashworth, J. B., and J. Hopkins. 1995. *Aquifers of Texas*. Texas: Texas Water Development Board. TWDB, Report 345.

Ashworth, J. B. 2001. *Bone Spring-Victorio Peak Aquifer of the Dell Valley Region of Texas*. Ch. 10, *Aquifers of West Texas*. Texas: Texas Water Development Board. TWDB, Report 356.

Bennett, J. B. 2002. Concepts of ground-water recharge in the Trans-Pecos Region, Texas. The Geological Society of America Conference. April 12, 2002. Texas: Sul Ross State University.

Boghici, R., D. Coker, and M. Gueva. 1999. *Changes in groundwater condition in Parts of the Trans-Pecos, Texas 1988-1998.* Texas: Texas Water Development Board. TWDB, Report 348.

Clarke, J. U. 1998. Evaluation of censored data methods to allow statistical comparisons among very small sample with below detection limit observations. *Environmental Science and Technology* 32: 177-183.

Fetter, C. W. 1988. Applied Hydrology, 2nd Edition. Ch. 9, Water Chemistry. Columbus: Merrill Publishing Company.

Friedberg, R. 2003. West Texans cool to water proposal. *Odessa American*, November, 21. [newspaper online]; available from http://www.oaoa.com; Internet; accessed 4 May 2006.

Hopkins, J. 1995. *Water quality in the Edwards-Trinity (Plateau) Aquifer, Edwards Plateau and Trans-Pecos, Texas.* Texas: Texas Water Development Board. TWDB, Hydrological Atlas No. 3.

Huston, R. J., R. B. Marquez, and J. M. Baker. 1999. *Surface water quality monitoring procedures manual.* Texas: Texas Natural Resource Conservation Commission. TNRCC, GI-252.

Hutson, S. S., N. L. Barber, J. F. Kenny, K. S. Linsey, D. S. Lumia, and M. A. Maupin. 2004. Estimated use of water in the United States 2000. *U.S. Geological Survey Cir.* 1268 [journal online]; available from http://pubs.usgs.gov/circ/2004/circ1268/index.html; Internet; accessed 2 April 2005.

Jones, I. C. 2001. *Cenozoic Pecos Alluvium Aquifer. Ch. 9, Aquifers of West Texas.* Texas: Texas Water Development Board. TWDB, Report 356.

Jones, R. P., and J. U. Clarke. 2005. *Analytical chemistry detection limits and the evaluation of dredged sediment.* Engineering Research and Development Center. ERDC, ERDC/TN EEDP-04-36.

LBG-Guyton Associates. 2001. "*Igneous aquifer system of Brewster, Jeff Davis and Presidio Counties, Texas,*" [webpage]; available from http://www.riocog.org/EnvSvcs/FWTWPG/publishe.htm; Internet, accessed 28 April 2005.

Mace, R. E. 2001. *Aquifers of West Texas: an overview. Ch. 1, Aquifers of West Texas.* Texas: Texas Water Development Board. TWDB, Report 356.

Madden, W. B., and C. D. Pederson. 2002. *Water for Texas.* Texas: Texas Water Development Board. TWDB, Report No. GP-7-1.

Mouser, P. J., D. M. Rizzo, W. F. M. Rolling, and B. M. Van Breukelen. 2005. A multivariate statistical approach to spatial representation of groundwater contamination using hydrochemistry and microbial community profiles. *Environmental Science Technology* 39, no. 19: 7551-7559.

Muller, D. A., and R. D. Price. 1979. *Ground-water availability in Texas-estimates and projection through 2030.* Texas: Texas Department of Water Resources. TDWR, Report 238.

Murray, C. R., and E. B. Reeves. 1977. *Estimated use of water in the United States in 1975*. United State Geological Survey. U.S. Geological Survey Circ. Report 765.

Price, R. D., M. A. Hart, M. L. Ambrose, D. Prescott, and C. Lancaster. 1989. *Ground-Water Quality of Texas*. Texas: Texas Water Development Board. TWDB, Report 89-01.

Schmidt, R. H. 1995. *The climate of Trans-Pecos Texas*. Ch. 11, *The changing climate of Texas: predictability and implications for the future*. College Station: Texas A&M GeoBooks.

Smith, R. K. 1993. *Handbook of environmental analysis*. New York: Genium Publishing Corporation.

Spearing, D. 1991. *Roadside geology of Texas*. Ch. 6, *West Texas*. Missoula: Mountain Press Publishing Company.

S-Plus 6.1. 1998. 2002 Insightful Corporation [CD-ROM], Lucent Technologies, Inc. (Software)

Tauler, R., D. Barcelo, and E. M. Thurman. 2000. Multivariate correlation between concentrations of selected herbicides and derivatives in outflows from selected U.S. Midwestern reservoirs. *Environmental Science & Technology* 34, no. 16: 3307-3314.

Todd, D. K. 1980. *Groundwater hydrology*. Second edition. John Wiley & Sons Inc: Canada.

Uliana, M. M. 2001. The *geology and hydrogeology of the Capitan Aquifer: a brief overview*. Ch. 11, *Aquifers of West Texas*. Texas: Texas Water Development Board. TWDB, Report 356.

Uliana, M. M., and J. M. Jr. Sharp. 2001. Tracing regional flow to major springs in Trans-Pecos Texas using geochemical data and geochemical models. *Chemical Geology* 170: 53-72.

Uliana, M. M. 2005. Identifying the sources of saline groundwater contamination using geochemical data and modeling. *Environmental & Engineering Geoscience* 11, no. 2: 107-123.

Uliana, M. M, J. L. Banner, and J. M. Sharp. 2006. Regional groundwater flow paths in Trans-Pecos, Texas inferred from oxygen, hydrogen, and strontium isotopes. *Journal of Hydrology* (in press).

United States Geological Survey (USGS), "Monitoring the water quality of the Nation's large rivers," Rio Grande NASQAN Program [webpage]; available from http://water.usgs.gov/nasqan/progdocs/factsheets/riogfact/engl.html; Internet, accessed 15 January 2006.

Washington, D., and Perez, D. "Border experts flow into city for water conference," *El Paso Times*. May 30, 2001.

Williams, C. S., and T. H. Bonner. 2006. Habitat associations, life history and diet of the Sabine Shiner Notropis sabinae in an East Texas drainage. *American Midland Naturalist* 155: 84-102.

YSI Incorporated, n.d. *600 Multi-Parameter water quality monitor, instruction manual.*

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