Hydrologic Investigation in the Toyah Basin near Balmorhea, Texas

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I. ABSTRACT

The purpose of this hydrogeologic investigation was to determine the flow regimes affecting the springs of the Toyah Basin in and around Balmorhea, Texas. This was accomplished by determining well water levels, gauging discharges of springs, and chemical analyses of selected spring and well water. The results were compared to the data collected in previous investigations. The data were collected during a field study conducted from June 1-4, 1995 and supports previous investigations which suggest a mixture of local and regional groundwater flow regimes. This conclusion is supported by conductivity and total dissolved solids data. Potentiometric surface elevations continue to decline in comparison to previous UT Field Hydrology class reports in this area. The potentiometric map indicates a southwest to northeastern flow direction for the study area.

II. INTRODUCTION and OBJECTIVES

This field study encompasses the area around Balmorhea, Texas, in southwest Reeves and northern Jeff Davis Counties and the surrounding region in the Toyah Basin. The main objective of the study is to accurately characterize the flow regimes responsible for the numerous springs in this portion of Reeves County and northeast Jeff Davis County. In order to attain this goal, three types of data were collected during the field study:

1) Water levels, in order to construct a potentiometric surface for the Balmorhea area;
2) Chemical analysis of eight springs in the region; in order to characterize the spring's geochemical characteristics.
3) Spring discharge at each spring system; in order to measure spring disharge rates, stream flow measurements were taken using a flow meter or weir.

The springs in the study area represent a vital life-line through irrigation for the various forms of agricultural practices. These agricultural activities, such as cattle ranching and cotton, make up the economic foundation of the area. Consequently, understanding the nature of the flow regimes that control the spring discharge, and their associated chemistry, is relevant to the economic well being of the individuals located in the southwest portion of the Toyah Basin.

The demand exerted by the surrounding agriculture on the springs has been complicated by the presence of the Comanche Spring Pup Fish in two major springs of the basin. The Pup Fish is protected by the Federal Government through the Endangered Species Act because this particular species is found only in San Solomon Spring and Phantom Lake Spring, both located west of Balmorhea. The Pup Fish has also been reported to exist in Giffin Spring but the fish is only protected by the Endangered Species Act in San Solomon and Phantom Springs. Due to the Endangered Species Act, discharge from these springs must be maintained at a level high enough to ensure the survival of the endangered fish. (Tom Johnson, personal communication) Unfortunately, irrigation requirements in the basin have increased with augmented land use and the Toyah Basin is currently entering its fourth year of drought. As a result of decreased recharge due to the prolonged drought, increased discharge from enhanced land use, and the presence of an endangered species, an accurate analysis of the flow regimes that drive the system of springs in the Toyah Basin is vital.

III. REGIONAL GEOLOGY and GEOHYDROLOGY

The study area is located north of the Davis Mountains and east of the Apache Mountains in the Toyah Basin of West Texas. The surfical geologic units in the area include Quaternary age alluvial gravels and clays, which vary in thickness from 0 to 475 m (1500 ft) (LaFave 1987) and cover most of the predominantly flat land surface. Tertiary age volcanic rocks are also present to the southeast and include the Limpia Formation (100 m/300 ft thick), Star Mountain Rhyolite (167 m/496 ft thick), and the Huelster Formation (131 m/400 ft thick). Also present and underlying the aforementioned units are Lower and Upper Cretaceous age limestones, such as the Buda Limestone (32 m/100 ft thick) and Boquillas Formation (Barnes 1982). The Buda Limestone is subject to extensive dissolution or karstification and appears to play a major role in the hydrogeology of the study area. The presence of a large sinkhole 1.3 miles west of the Reeves/ Jeff Davis County line on US 290 supports the presence of an active flow regime. It may appear to serve as a discrete point of local recharge. Likewise, Phantom Lake Spring, which issues from a large opening in a limestone bluff, is located in close proximity to a large dissolution feature and surrounded by caves.

The springs constitute one of the most salient hydrological features of the Balmorhea area and the contiguous Davis Mountains. The Balmorhea area contains six "major" springs, in addition to various smaller springs which appear intermittently along the Toyah

Creek stream bed during periods of heavy rainfall. The six large springs are San Solomon, Phantom Lake, Giffin, Saragosa, West Sandia, and East Sandia. Phantom Lake springs have been characterized as artesian springs, issuing from Lower Cretaceous limestones. The remaining springs have been classified as "gravity" springs which emanate from the alluvial gravels overlying the Cretaceous limestones (White et al., 1938). Much of the water from the springs is diverted into small canals and used to irrigate surrounding farmland. Additional springs discharge farther southwest and in close proximity to the Davis Mountains, including Catfish Spring and Big Aguja Canyon Springs (see map). The Big Aguja Canyon Spring provides the municipal water supply for the town of Toyah (Wes Elliot, personal communication).

The largest spring in the Balmorhea area, San Solomon Springs, flow into the Balmorhea State Park pool. Giffin Springs, the second most prolific spring in terms of discharge, is located just north across the highway from San Solomon Springs. Phantom Lake Spring, which represents the third largest of the springs, is located on the northwestern edge of a solution feature approximately seven kilometers west-southwest of the San Solomon Spring (LaFave and Sharp, 1987). The combined discharge of these three springs accounts for the vast majority of spring flow in the Balmorhea study area. Saragosa Spring is no longer flowing, and the flow of the other two springs is small by comparison. The locations of these remaining springs are provided on the map accompanying this report.

Although various investigations have been conducted, such as White et al. (1941), Couch et al. (1978), and LaFave and Sharp (1987), the exact origins and proportions of recharge to the Balmorhea springs are yet uncertain. Traditionally, recharge of the springs has been attributed to precipitation in the nearby Davis Mountains. According to this hypothesis, water seeps through overlying volcanic rocks and river gravels into the Lower Cretaceous limestones along the southwest limb of the Star Mountain Anticline. This water, which is confined by the Upper Cretaceous strata, moves downdip and discharges at the springs, where displacement of the Upper Cretaceous units has occurred.

Couch et al. (1978) have proposed an alternative hypothesis, suggesting that a substantial portion of the water discharging from the springs may originate in the Capitan Reef rocks of the Apache Mountains. This idea is predicated on water chemistry, water budget data, regional trends in structural geology, and regional flow patterns in the southern portion of the Salt Basin. According to the authors, the sodium-chloride-sulfate type water found in the Balmorhea springs and Toyah Basin alluvial gravels bear a chemical signature strikingly similar to that found in the Capitan Reef, but distinctly different from groundwater associated with the Davis Mountains. This fact, coupled with the conspicuous alignment of southeast-trending normal faults between the Apache Mountains and the northwestern flank of the Davis Mountains (a possible flow conduit), suggests that the springs at Balmorhea could potentially be a discharge site for water moving eastward from the southern portion of the Salt Basin in the Apache Mountains to the Lower Cretaceous limestones in the Toyah Basin. Steady discharge from the springs could possibly be attributed to steady flow of water through a regional scale carbonate aquifer. (LaFave and Sharp (1987))

It is important to note that during periods of relatively heavy precipitation, White et al. (1941) observed rapid increases in spring discharge, turbidity, and decreases in salinity and temperature. However, more data needs to be collected. This suggests that recharge of the springs may also be governed by an additional storm component which is more local in nature. Under arid conditions, the contribution of such a component to spring flow could probably be considered negligible. Under normal conditions, the Balmorhea area typically receives 12 to 13 inches (32 to 35 cm) of rainfall each year. The last four years have been exceptionally dry, with less than 5 inches of rain falling each year (Wes Elliot and Dave Lovett, personal communication).

Although the above discussion focuses primarily on recharge to the various springs of the Balmorhea area, it is important to keep in mind that the study area does in fact contain a shallow alluvial aquifer. The level of this local aquifer apparently fluctuates with the level of the Balmorhea Lake Reservoir (Freddy Schreier, personal communication), suggesting that local rainfall provides much of the recharge. Additional sources of recharge to this alluvial aquifer are probably spring-related and need further study. (i.e. direct infiltration of spring water (Kirschenmann et al., 1990) or loss of water from irrigation canals)

IV. METHODOLOGY

Water Table Elevation

The majority of water table elevations were measured with the use of a Geo Tech E-line with a graduated cable marked in tenths of a foot. The E-line is an open circuit that activates a sounder once it comes in contact with water because the circuit is completed. In a few cases where the well bore opening was too small for the E-line tool to safely insert, a steel tape with a homemade popper attachment made from a key and plastic bottle cap was used to secure the depth to the water table. In either case, the E-line or tape was lowered down the well and the depth to the water table was recorded. With this measurement, the distance from the land surface elevation to the top of the casing for the well was subtracted, giving the actual depth to the water table. Elevation head was then calculated by subtracting the depth to the water table from the surface elevation approximated from USGS topographic maps.

Stream Flow Measurement

Flow rates where determined as close to the springs orifice as possible using a Global Water Flow Meter (Golden Rod), which measures water velocity in ft/sec. In one case where flow velocity was too slow to be detected by the Golden Rod, a homemade flume was constructed out of two 2x4s that constricted the flow and subsequently increased the flow velocity of the stream so the flow meter could measure the velocity (see Appendix A, p.1). The average flow is determined by placing the Golden Rod at 60% of the stream depth at a particular point in the transect measured perpendicular to stream flow. Discharge is then calculated using the midsection method:

$$Q = \sum W \cdot D \cdot (avgvel) \qquad (1)$$

Q ≡ spring discharge
W ≡ width of the stream at the measuring point
D ≡ depth from water surface to streambed
avgvel ≡ average velocity of stream

At San Solomon Spring and Phantom Lake Spring, a rectangular weir was used to calculate discharge, in this case the following formula was used:

$$Q = \tfrac{1}{3}(L - 0.2H)H^{3/2} \qquad (2)$$

Q ≡ discharge
L ≡ length of the weir crest
H ≡ head of the backwater above the weir crest

Chemical Analysis

Dissolved oxygen (D.O.) was determined through sampling the spring water with Chemetrics R-7512 vacu-vials and comparing the color of the sample to a standardized color chart to find the D.O. level of the water.

Specific conductivity was measured in situ using a Hanna Instruments Comment 2 Conductivity Meter with an automatic temperature compensation (ATC). Total dissolved solids (TDS) where then calculated utilizing the following relationship:

Temperature and pH were measured in situ with an Orion 250A hand held meter.

Filtered samples were required when performing alkalinity test and when anion and cation samples where collected. Two methods of filtering where used. The first used a Mountain Science Research 0.2 micrometer filter with a 12 V Reversible Variable Speed Peristaltic Pump. The second method employed a 25 ml syringe with two filters: a 0.45 micrometer nylon Camco filter and a Gelman Glass Acrodisco filter. The anion samples were collected in a 60 ml acid cleaned bottle and the cation samples were placed in 30 ml acid cleaned bottle. The cation samples were treated with three drops of concentrated HNO_3 in order to prevent the precipitation of metals from the solution. Finally, all of the water samples were labeled, sealed with parafilm to prevent leakage and contamination, and placed in an ice chest for storage to inhibit bacterial growth.

Alkalinity was determined by titrating 25 ml of filtered sample with 0.1N HCL to a final pH of 4.5. The bicarbonate component of the water sample was then calculated by the amount of acid added to the sample. This may be calculated with the following series of equations:

$$4V_a = A \tag{4}$$

$$61 \cdot A = HCO_3^-\left({}^{mg}\!/\!_{L}\right) \tag{5}$$

V_a ≡ volume of 0.1N HCl added to sample (ml)
A ≡ alkalinity (meq/L)
4 ≡ constant for a 25 ml sample
61 ≡ constant for formula weight of HCO_3

V. RESULTS

The elevation heads are calculated from the well levels and the topographic surface elevation. The heads were then plotted on a map of the study area in order to create an accurate representation of the potentiometric surface. This map of the water table indicates a general direction of groundwater flow from the southwest to the northeast. There is no apparent depression or drawdown of the potentiometric surface around the town of Balmorhea as was initially expected due to the abundance of water wells in town.

Water chemistry was performed in the field for seven springs and four wells. High specific conductivities were observed in Giffin, East Sandia, West Sandia, San Solomon, and Phantom Lake Springs. This included wells #31 and #13. In comparison, Catfish Spring, Big Aguja Spring, well #32, and well #35 had low specific conductivities. No trends clearly manifest themselves for pH, temperature, dissolved oxygen, and alkalinity.

Discharge measurements are reported for all of the eight springs examined during the course of this study. San Solomon and Giffin Springs have the greatest discharge. There appears to be no significant trend when comparing discharges measured for this report versus similar discharges measured in previous UT studies (Bauer et al., 1992; Kirschenmann et al., 1990). This may be attributed to different methodologies employed for stream gauging, different locations at which measurements of stream velocity were taken, and precipitation events.

VI. INTERPRETATION and CONCLUSIONS

A comparison of spring discharge measurements recorded during this investigation with the previous measurements from 1990 and 1992 reveals some obvious discrepancies. The discharge value recorded at San Solomon Spring is substantially lower than that values obtained in 1990 and 1992. However, the discharge measured at Giffin Spring is greater, suggesting an anomaly of some kind because the proximity of San Solomon and Giffin Springs to one another and their similar water chemistry indicate that they are probably recharged by the same source. This anomaly might be attributed to differences in methodology employed by the various groups measuring discharge. Different flow meters were used (digital flow meter as opposed to a pygmy meter). In addition, spring discharge could have been measured at different sites in relation to the springs. Such might cause differences in discharge measurements.

Of tantamount importance to monitoring temporal fluctuations in stream discharge is determining the actual source of recharge to the springs. Several hypotheses explaining the origin of spring waters have been proposed, including recharge from precipitation in the Davis Mountains and infiltration of ground water from the Capitan Reef in the Apache Mountains (Couch, 1978; LaFave and Sharp, 1987). Based on research and observations made during the course of this investigation, the latter interpretation appears to be more feasible. That is to say, it seems reasonable to conclude that recharge of the major artesian springs near Balmorhea (San Solomon, Giffin, and Phantom Lake) is closely tied to flow through a regional carbonate aquifer and is not the result of precipitation in the Davis Mountains with subsequent seepage into underlying Cretaceous limestone strata. This conclusion is based on geochemical data and observations/knowledge of the local and regional geology.

Currently available geochemical data seems to provide compelling evidence that spring flow is primarily being recharged by waters originating in carbonate rocks to the west of Balmorhea, possibly the Permian limestones of the Capitan reef in the Apache Mountains or Wildhorse Flat. (Couch, 1978). Additional isotopic and trace-element analyses are necessary to support this conclusion, but the limited specific conductivity data obtained during this investigation seem to support the initial findings of LaFave and Sharp (1987). Specific conductivity values for Balmorhea spring waters, which are an indirect indication of total dissolved solids, exceed conductivity values for the Big Aguja Canyon and Catfish Spring waters by an order of magnitude. Based on this disparity and the assumption that the latter two springs contain waters typical of the Davis Mountain hydrological regime, one may conclude that the Davis Mountain waters are not the primary source of recharge to the Balmorhea springs. In addition, alkalinity value obtained for Catfish Spring was noticeably lower than values obtained for the various Balmorhea springs, perhaps providing yet additional evidence of differences between the waters. Thus, like data collected by LaFave and Sharp (1987), specific conductivity values obtained during this investigation seems to suggest a fundamental difference between Davis Mountain and Balmorhea spring waters.

Additional clues as to the origin of the Balmorhea spring waters can be found in local geologic features which may be expressions of some larger-scale structural or geologic trends that dominate the regional hydrogeology. Features include the numerous examples of dissolution of the Lower Cretaceous limestones in the Balmorhea area. Some of the more dramatic examples include the presence of a large solution feature near the Phantom Lake Spring (LaFave and Sharp, 1987) and a substantial sinkhole just northwest of Phantom Lake Spring, approximately 1.3 miles west of the Reeves/Jeff Davis County line. In addition, well owner, Rick Moon (Well #30), reported that while installing his 125 foot well, the drillers penetrated a large limestone cavern. Recent exploration of the Phantom Lake Spring orifice by a team of scuba divers revealed that the opening represents the outlet of a deep and extensive subterranean cave network. The team had penetrated the cave interior to a distance of almost 3,000 feet and a depth of 90 feet before prematurely ending the expedition due to a lack of time. Additional exploration is required before the cave can be adequately mapped (Tom Johnson, personal communication). This discovery, coupled with the numerous other examples of solution features in the Lower Cretaceous limestones, suggests that extremely widespread, regional karstification is a strong possibility and may ultimately be controlling steady flow to the springs. Rapid recharge also occurs through some of these local solution features. Firsthand account of local well owner, Rick Moon, and careful inspection of the sinkhole reveals that water clearly flows into the sinkhole during local rainfall events, providing a source of local recharge to the springs and the deeper limestone aquifer. This coincides with the so-called storm or "flash" component of recharge described by LaFave and Sharp (1987). However, it is important to keep in mind that recent precipitation in the Toyah Basin has been scarce and that some regional source of water must be recharging the springs.

In regard to the local alluvial aquifer, a noticeable decrease in water levels has clearly occurred during the past five years (based on a comparison with the previous two GEO 382 reports). This can logically be attributed to abnormally low rainfall amounts during the past three to four years. The fact that water levels tend to fluctuate or coincide with the level of Balmorhea Lake further suggests that local rainfall is the primary source of recharge to the aquifer. The desiccation of Saragosa Spring, a locally recharged gravity spring, provides further testament to this conclusion.

Another possible source of recharge to the alluvial aquifer could be infiltration by spring water (i.e. either by direct seepage from the springs or by loss of water from the irrigation canals). This might explain the fact some wells have gone completely dry while others still contain some water and are used for lawn irrigation or for livestock.

VII. ACKNOWLEDGMENTS

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Appendix A

Spring Discharge Data

Location	v (ft/s)	w (ft)	d (ft)	Q (cfs)	total Q (cfs)
Giffin Spring	1.60	0.98	0.95	1.50	
	1.70	1.97	1.05	3.51	
	1.40	2.95	1.05	4.34	**9.35**
West Sandia Spring	3.50	0.98	0.15	0.52	
	5.00	1.97	0.29	2.83	**3.35**
San Solomon Spring					
rectangular wier	L=8.2ft	H=1.12ft		3.15	**3.15**
main canal	1.90	5.25	1.85	18.45	**18.45**
small canal	0.10	0.98	0.40	0.04	
	0.10	1.97	0.40	0.08	**0.12**
Lower East Sandia Spring	0.75	0.66	0.50	0.25	
	0.90	1.31	0.40	0.47	**0.72**
Catfish Spring	0.70	0.52	0.51	0.19	**0.19**
Phantom Lake Spring	0.65	0.49	0.72	0.23	
	0.65	0.98	0.72	0.46	
	0.60	1.48	0.72	0.64	
	0.60	1.97	0.72	0.85	
	0.50	2.46	0.72	0.89	
	0.50	2.95	0.70	1.03	**4.10**
Big Aguja Spring					
near spring orifice	2.50	1.64	0.21	0.85	
	0.05	2.13	0.24	0.03	
	0.01	2.62	0.22	0.01	**0.88**
61m from orifice	0.01	1.97	0.24	0.00	
	0.01	2.95	0.34	0.01	
	0.15	3.94	0.33	0.20	
	0.01	5.25	0.10	0.01	
	0.01	6.23	0.49	0.03	
	0.30	7.22	0.37	0.81	
	0.01	8.20	0.24	0.02	
	0.70	9.19	0.49	3.16	
	0.05	10.17	0.30	0.15	**4.39**
136m from orifice	0.30	0.33	0.31	0.03	
	0.25	1.15	0.28	0.08	
	0.65	1.97	0.31	0.40	
	0.50	2.79	0.33	0.47	
	0.60	3.61	0.39	0.85	
	1.15	4.43	0.36	1.83	
	0.70	5.25	0.37	1.37	
	0.60	6.07	0.36	1.31	
	0.40	6.89	0.27	0.74	
	0.00	7.71	0.12	0.00	**7.09**
Saragosa Spring	0.00	0.00	0.00	0.00	**0.00**

v=velocity
w=width of stream at velocity measurement
d=60% of total stream depth
Q=discharge

Spring Discharge Data

Location	v (m/s)	w (m)	d (m)	Q (m3/s)	total Q (m3/s)
Giffin Spring	0.49	0.30	0.29	0.042	
	0.52	0.60	0.32	0.099	
	0.43	0.90	0.32	0.123	0.265
West Sandia Spring	1.07	0.30	0.05	0.015	
	1.52	0.60	0.09	0.080	0.095
San Solomon Spring					
rectangular wier	L=2.50m	H=0.34m		0.161	0.161
main canal	0.58	1.60	0.56	0.522	0.522
small canal	0.03	0.30	0.12	0.001	
	0.03	0.60	0.12	0.002	0.003
Lower East Sandia Spring	0.23	0.20	0.15	0.007	
	0.27	0.40	0.12	0.013	0.020
Catfish Spring	0.21	0.16	0.16	0.005	0.005
Phantom Lake Spring	0.20	0.15	0.22	0.007	
	0.20	0.30	0.22	0.013	
	0.18	0.45	0.22	0.018	
	0.18	0.60	0.22	0.024	
	0.15	0.75	0.22	0.025	
	0.15	0.90	0.21	0.029	0.116
Big Aguja Spring					
near spring orifice	0.76	0.50	0.06	0.024	
	0.02	0.65	0.07	0.001	
	0.00	0.80	0.07	0.000	0.025
61m from orifice	0.00	0.60	0.07	0.000	
	0.00	0.90	0.11	0.000	
	0.05	1.20	0.10	0.006	
	0.00	1.60	0.03	0.000	
	0.00	1.90	0.15	0.001	
	0.09	2.20	0.11	0.023	
	0.00	2.50	0.07	0.001	
	0.21	2.80	0.15	0.090	
	0.02	3.10	0.09	0.004	0.124
136m from orifice	0.09	0.10	0.10	0.001	
	0.08	0.35	0.08	0.002	
	0.20	0.60	0.10	0.011	
	0.15	0.85	0.10	0.013	
	0.18	1.10	0.12	0.024	
	0.35	1.35	0.11	0.052	
	0.21	1.60	0.11	0.039	
	0.18	1.85	0.11	0.037	
	0.12	2.10	0.08	0.021	
	0.00	2.35	0.04	0.000	0.201
Saragosa Spring	0.00	0.00	0.00	0.000	0.000

v=velocity
w=width of stream at velocity measurement
d=60% of total stream depth
Q=discharge

Chemical Analyses

Location	pH	S.C. (mS/cm)	TDS (mg/l)	Temp. (°C)	DO (ppm)
Giffin Spring	7.30	3.30	2310	26.4	7
West Sandia Spring	7.44	4.35	3045	20.4	5.5
Well #31	7.18	1.56	1092	24.8	
Phantom Lake Spring	7.12	3.57	2499	25.2	1.5
San Solomon Spring	7.33	3.25	2275	23.9	4
Well #13	7.01	3.76	2632		
East Sandia Spring					
near orifice	7.10	4.85	3395	22.8	5
streambed		4.46	3122		
Catfish Spring					
streambed		0.39	273	23.4	7
pond	7.21	0.38	266	29.6	
Well #32					
stock tank		0.26	182		
pump	7.27	0.30	210	23.3	
Well #35	7.07	0.34	238	22.2	
Big Aguja Spring					
near orifice	7.30	0.31	217		
61m from orifice	7.32	0.32	224	21.4	
136m from orifice	7.79	0.44	308	23.1	

S.C.=specific conductivity
TDS=total dissolved solids
Temp.=temperature
DO=dissolved oxygen

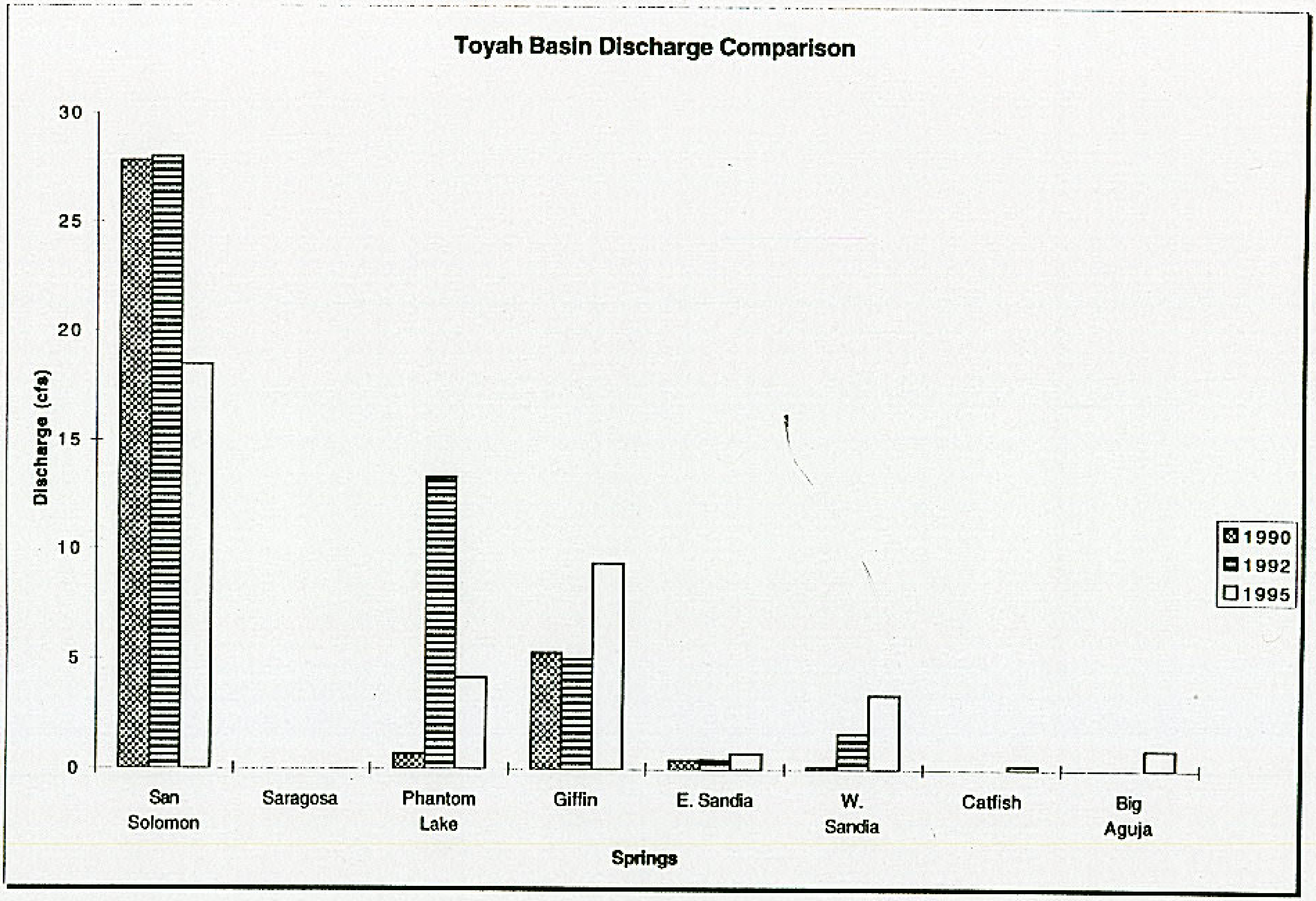
Chemical Analyses

	Alkalinity Titrations						
Location	Endpoint pH	0.1 N HCl added (ml)	Sample volume (ml)	Alkalinity (meq/l)	HCO_3^- (mg/l)		
Giffin Spring	4.48	2.27	50	4.54	276.94		
West Sandia Spring	4.44	1.42	25	5.68	346.48		
Well #31	3.98	1.00	25	4.00	244.00		
Phantom Lake Spring	4.48	1.14	25	4.56	278.16		
San Solomon Spring	4.50	2.40	50	4.80	292.80		
Well #13	4.45	2.22	50	4.44	270.84		
East Sandia Spring							
near orifice	4.45	2.52	50	5.04	307.44		
streambed							
Catfish Spring							
streambed	3.93	0.95	25	3.80	231.80		
pond							
Well #32							
stock tank							
pump	4.43	0.70	25	2.80	170.80		
Well #35	4.44	0.75	25	3.00	183.00		
Big Aguja Spring							
near orifice							
61m from orifice							
136m from orifice							

S.C.=specific conductivity
TDS=total dissolved solids
Temp.=temperature
DO=dissolved oxygen

Well Level Data

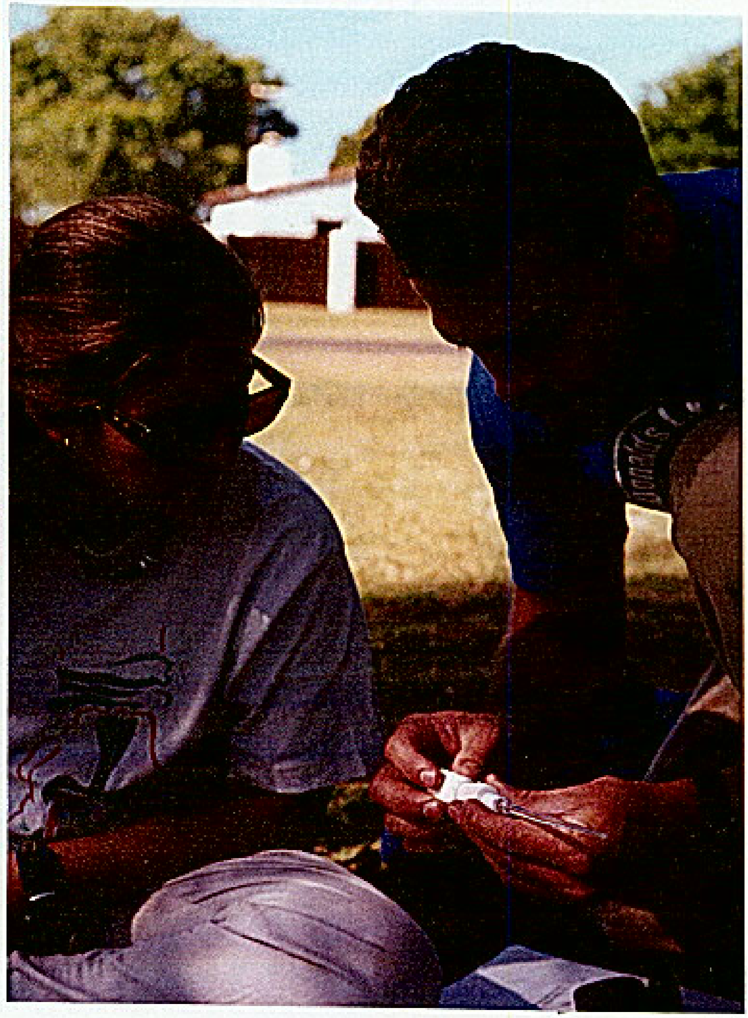
Well	Depth to water from top of casing (ft)	Casing Height (ft)	Depth to water from ground level (ft)	Surface Elevation (ft)	Elevation Head (ft)	Description
1	20.4	0.7	19.7	3275	3255.26	
2	>19.8	1.2	>18.6	3278	>3259.35	
3	39.3	3.0	36.3	3260	3223.70	dry
4	>18.0	0.0	>18.0	3250	>3232.00	dry
5	16.5	0.0	16.5	3239	3222.50	
6	18.1	0.0	18.1	3241	3222.90	
7	>11.8	0.0	>11.8	3242	>3230.20	dry
8	24.4	0.0	24.4	3257	3232.60	
9	>15.6	0.0	>15.6	3268	>3252.40	dry
10	23.2	0.7	22.4	3253	3230.56	
11	19.4	0.0	19.4	3250	3230.65	
12	18.0	0.7	17.3	3238	3220.68	below land surface
13	14.2	0.0	14.2	3185	3170.80	
14	14.9	0.0	14.9	3187	3172.10	dry
15	53.2	0.0	53.2	3211	3157.80	
16a	21.2	1.4	19.9	3161	3141.14	
16b	15.1	0.0	15.1	3163	3147.87	
17	13.9	0.0	13.9	3164	3150.15	
18	>8.8	0.0	>8.8	3160	>3151.25	dry
19	>10.3	0.5	>9.8	3183	>3173.20	moist
20	19.7	0.0	19.7	3167	3147.30	
21	58.7	0.0	58.7	3327	3268.30	
22	75.9	0.5	75.4	3345	3269.63	
23				3210		filled
24	>10.2	0.2	>10.0	3167	>3156.99	dry
25	20.0	1.1	18.9	3176	3157.12	
26	13.9	3.2	10.7	3162	3151.26	rainwater??
27	18.9	2.9	16.0	3158	3142.03	
28	20.3	0.5	19.8	3140	3120.25	dry
29	13.5	0.0	13.5	3335	3321.49	dry
30	101.2	0.0	101.2	3460	3358.79	karstic terrain
31	265.0	4.3	260.8	3580	3319.25	
32	111.6	3.0	108.6	3518	3409.40	
33				3187		filled
34				3191		filled
35				3509		no access



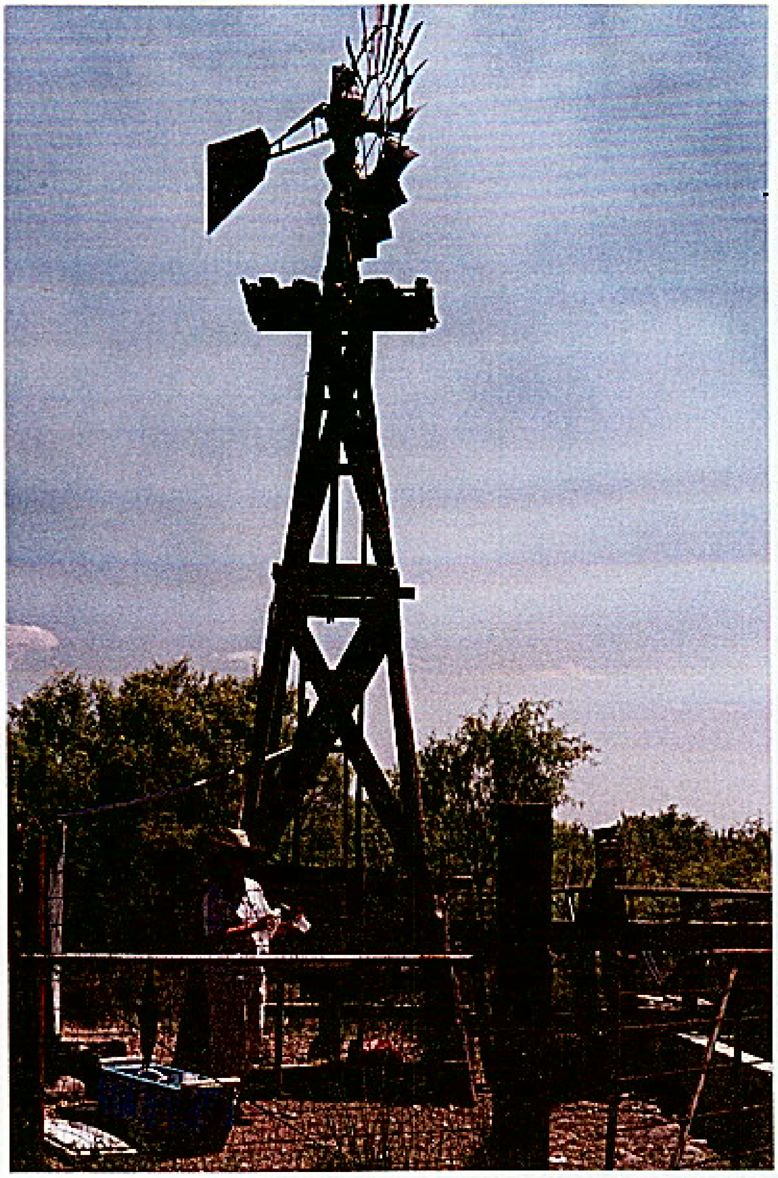
Toyah Basin Discharge Comparison
Discharge (cfs)
30
25
20
15
10
5
0
San Solomon
Saragosa
Phantom Lake
Giffin
E. Sandia
W. Sandia
Catfish
Big Aguja
Springs
1990
1992
1995

Appendix B

BELOW: Matt Uliana and Jennifer Wilson prepare to do alkalinity titrations for spring water chemistry at San Solomon Springs in Balmorhea State Park.



ABOVE: Matt Uliana is using the flowmeter in a field constructed flume to measure discharge at Catfish Springs



LEFT: Jennifer Wilson taking a water sample for chemical analysis at Well 13. The windwell design is frequently seen in this area, however, most are no longer used for water supply.

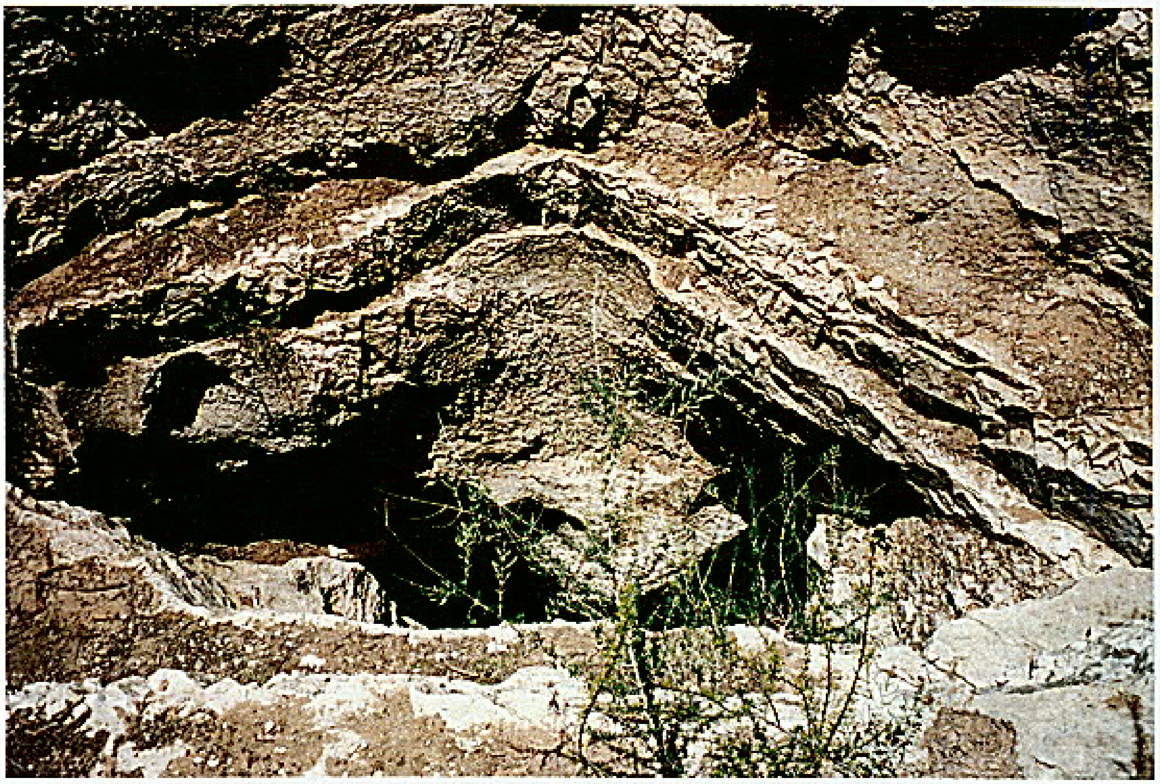
BELOW: Team members gauging the streamflow and discharge from a spring in the upper Big Aguja Canyon.

ABOVE: Early morning at San Solomon Spring-fed pool. The western edge of the main pool is seen in the foreground. The pool is a popular spot for divers from hundred of miles around.

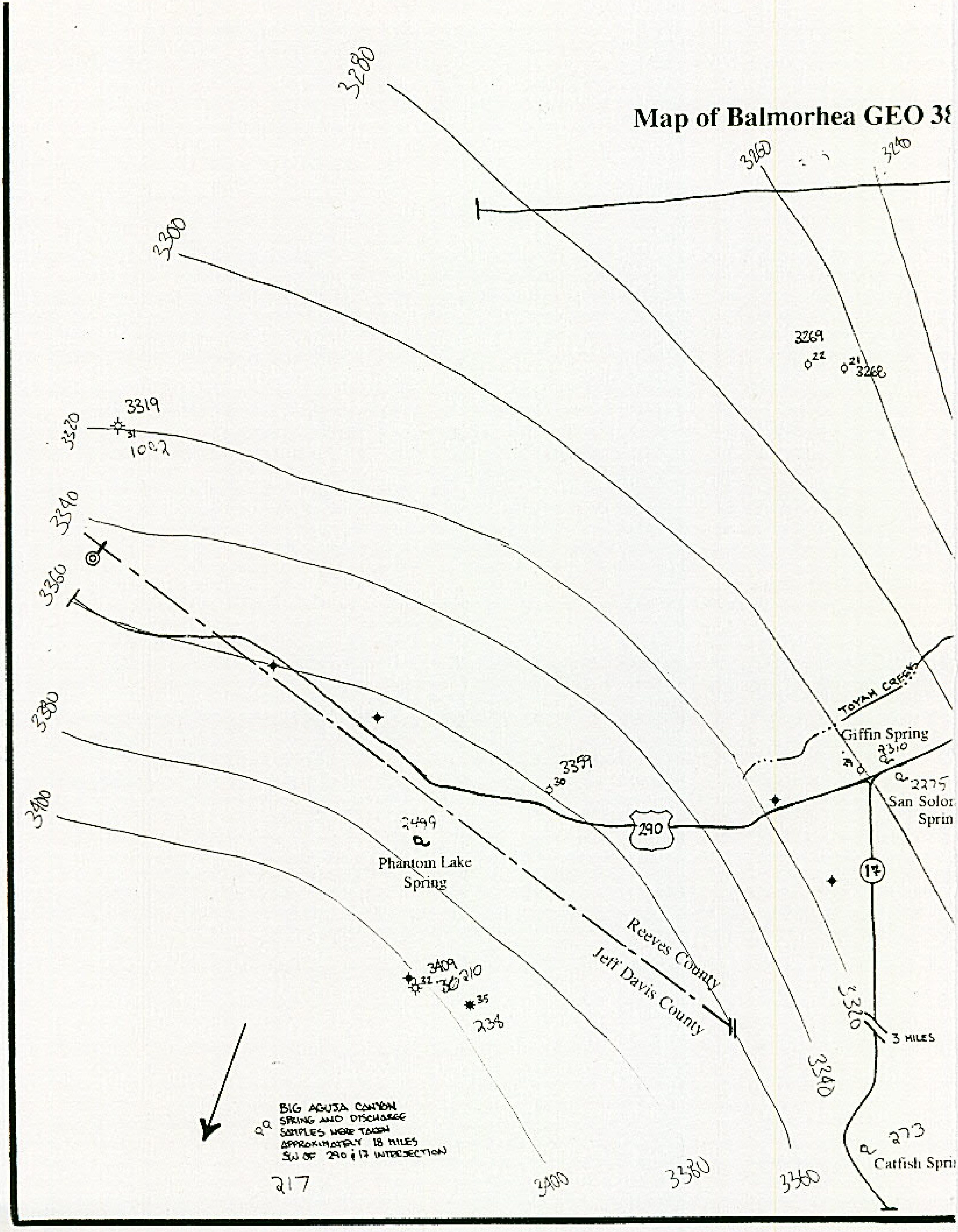
BELOW: Looking west across Catfish Springs pond. The spring feeds several other small surface ponds downstream that are all utilized for cattle and irrigation.

ABOVE: Phantom Lake Spring-fed irrigation canal. The view is looking east towards the cave opening. This area is a primary habitat of the endangered pup fish in the study area.

LEFT: Gated cave opening at Phantom Lake Spring. The cave is over 3000 feet long and is submerged up to 50 feet below the water table.



ABOVE: Sinkhole in Cretacious Buda Limestone at the western boundary of study area. This potential recharge feature presents many opportunities for additional research on groundwater aquifers and surface water interaction in the area. Exploration of the feature has been limited and locals indicate that there are several similar features in the same area.


Map of Balmorhea GEO 3
3280
3260
3240
3300
3269
3268
3319
3320
1002
3340
3360
3380
3400
TOYAH CREEK
Giffin Spring
2310
2375
San Solon
Sprin
3359
290
2499
Phantom Lake
Spring
17
Reeves County
Jeff Davis County
3409
238
3320
3 MILES
3340
273
Catfish Sprin
BIG AGUJA CANYON
SPRING AND DISCHARGE
SAMPLES WERE TAKEN
APPROXIMATELY 18 MILES
SW OF 290 & 17 INTERSECTION
217
3400
3380
3360

DRAFT

250 ft of head difference

20 ft interval

C Field Hydrology Study Area