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WATER BUDGET AND HYDROGEOLOGIC MODEL OF SPRING FLOW AT LIMESTONE HILL, ZZYZX DESERT STUDIES CENTER

A Thesis

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Master of Science

in

Geology

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Debra —

For you for christmas. —

I requested a copy of this thesis when doing a search for data on wells in the Preserve — and low and behold she sent me a copy

Jean

ABSTRACT

This study was performed to determine the source of recharge to MC Spring, which is home to the endangered Mohave tui chub. MC Spring is located at the Zzyzx Desert Studies Center, east of Limestone Hill. The water level in MC Spring is constant year-round, though the groundwater elevation in the adjacent playa aquifer of Soda Lake fluctuates seasonally as much as 1.5 meters and the elevation of the surface of MC Spring and groundwater in the alluvial aquifer is 1 to 2 meters higher than the elevation of the playa aquifer groundwater. The electroconductivity of the water in MC Spring and alluvial aquifer groundwater is an order of magnitude lower than the electroconductivity of the playa aquifer groundwater.

A hydrogeologic model was prepared using monitoring well data, alluvial aquifer recharge, and fracture measurements to determine a flow path to MC Spring. The evapotranspiration of Lake Tuende of 28.5 acre-feet per year was determined by the pumping data and used to calculate a water budget for MC Spring. The balanced water budget supports the observed stability of the surface elevation of MC Spring. Results of this study suggest that the source of water for MC Spring is alluvial and fractures in Limestone Hill provide a path for recharge.

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CHAPTER 1

INTRODUCTION

MC Spring is a modified, naturally occurring pond at the California State University's Desert Studies Center at Soda Springs, commonly referred to as Zzyzx. The spring is the only location known to naturally contain the Mohave tui chub (*Gila bicolor mohavensis*), which is listed as endangered (United States Fish and Wildlife Services 2007). The water level in MC Spring is constant year-round, suggesting that the source of recharge water to the spring balances the effects of evapotranspiration.

It is hypothesized that MC Spring is recharged through fractures in a limestone outcrop called Limestone Hill from the alluvial aquifer west of the hill (which is recharged from the southern extension of the Soda Mountains, known herein as Soda Mountain), rather than from the playa aquifer, which is recharged by the Mojave River system. The purpose of this project is to determine the groundwater recharge capacity in and around Limestone Hill as it impacts MC Spring, near the hill's base.

A comprehensive analysis of the local hydrogeology around Limestone Hill was performed to better understand the impact of local groundwater recharge sources on the spring habitat of the Mohave tui chub. The objective of this project was to synthesize existing data, gather more current data, and combine the results to produce a defensible hydrogeologic model of the source of recharge water to MC Spring.

Site Location and History

The Desert Studies Center (Zzyzx) is located on the southwestern edge of the Mojave Desert's Soda Lake, approximately 16 kilometers (km) (10 miles [mi]) south of Baker in San Bernardino County, Southern California. The center is situated at the base of Limestone Hill east of Soda Mountain (Figure 1). Historical use of this oasis of surface water is described by Duffield-Stoll (1994) and Mojave National Preserve (2006) and summarized below. Artifacts of human habitation have been dated as far back as 22,000 years. Explorers and surveyors rested at this and other areas across the desert in the late eighteenth and early nineteenth centuries. A U.S. Army post was established in 1859, and gold prospectors following the Mojave Road described the springs in 1863. A waystation was established after the withdrawal of the military in 1871; in 1885 gold and silver prospectors occupied the area. The Tonopah and Tidewater railroad arrived at Soda Springs in 1906 and operated until 1940. Soda was mined from the playa surface from 1907 through 1914. Thompson (1929) visited the site as part of a reconnaissance of the Mojave Desert in 1917 and 1919.

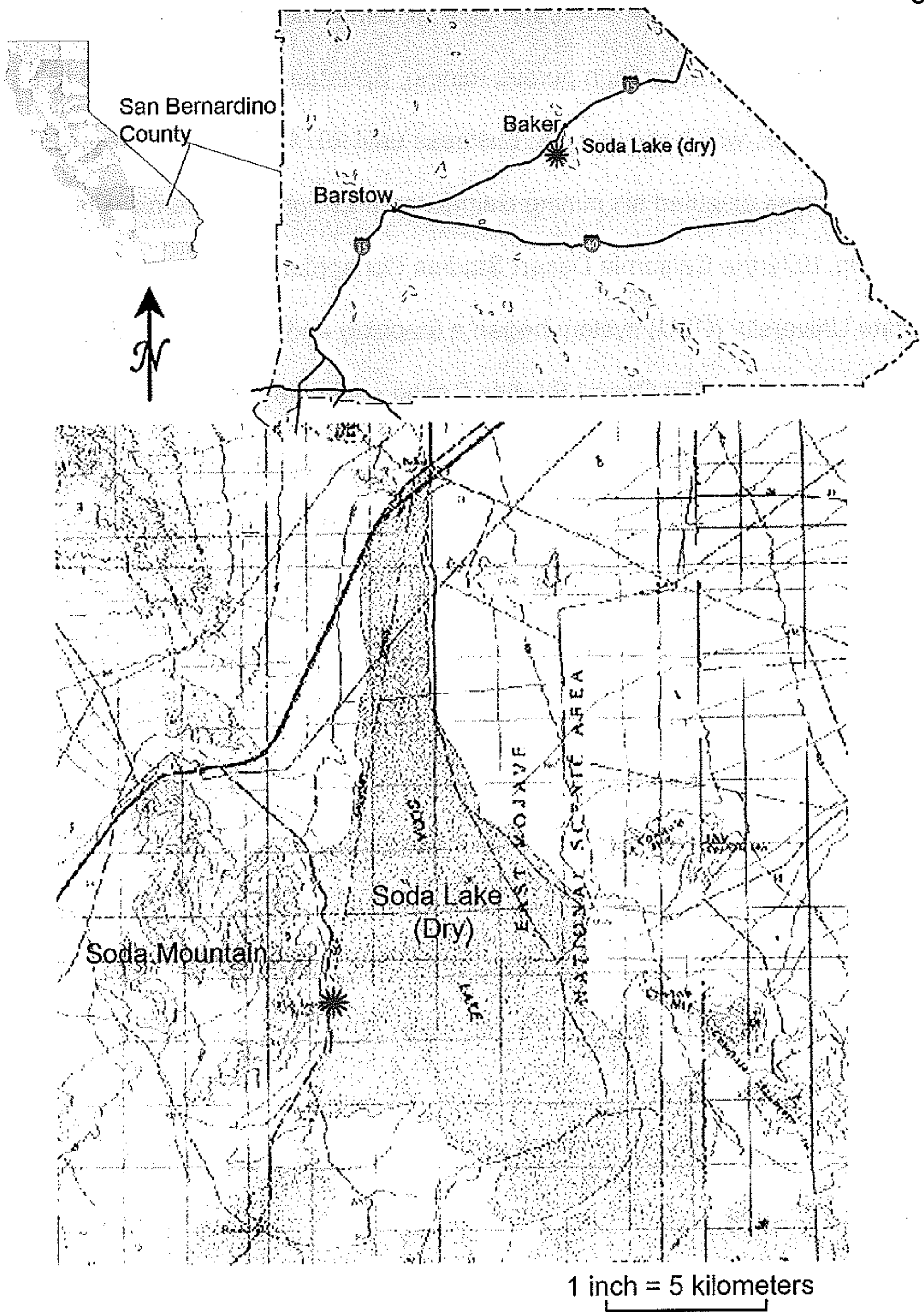


Figure 1. Zzyzx Desert Studies Center Location Map. Zzyzx is located on the western edge of the wedge-shaped Soda Lake (dry) in San Bernardino County, Southern California. Topography map from USGS quadrangle Soda Lake North.

In September 1944 Curtis Springer acquired the land by filing a mining claim. However, rather than pursue mining, Springer built a health resort that he named Zzyzx, which remained in business until 1974 when the Bureau of Land Management disputed his mining claims and had Springer and his wife evicted.

In 1976 the California Desert Studies Consortium program of the California State University (CSU) system began a teaching and research facility, which is still in operation. The Desert Studies Center is directed by Dr. William Presch and managed by Mr. Rob Fulton, both of CSU Fullerton. Students and educators avail themselves to the facilities available in this part of the Mojave Desert, where instruction subjects and research projects include biology, geology, anthropology, astronomy, and the history of the Mojave Desert.

Geologic Setting

The Mojave Desert contains some of California's oldest rocks, including Precambrian quartzite, dolomite, and gneissic rocks. Harvey and Wells (2003) described the area as tectonically stable and Grose (1959) indicated there was no evidence of recent activity on the thrust complex he called the Soda-Avawatz Fault. According to Butler (1984), all movement on this zone took place prior to 0.9 million years ago.

The southern end of the 19-km (12-mi) long, wedge-shaped Soda Lake playa is approximately 9.5 km (6 mi) wide (Figure 1). Salt deposits encrust the playa surface. Below the salty crust up to 1,070 meters (m) (3,500 feet [ft]) of gravel, sand, and clay playa deposits are underlain by bedrock (Dickey et al.1979; Muessig et al. 1957). Subsurface sediments suggest that intermittent lake conditions occurred as early as 22,000 years ago with sufficient flooding of the Mojave River (Enzel et al. 1992; Wells et al. 2003). North of the narrow northern end of Soda Lake, Silver Lake marks the terminus of the Mojave River (Enzel et al. 1992).

As a result of previous thrust faulting on the southern Death Valley Fault Zone (formerly referred to as the Soda-Avawatz fault) the Soda Mountains, which consist of Paleozoic limestone and Triassic to Jurassic granitics and metavolcanics (Grose 1959; Walker et al. 2002), rise steeply on the western edge of Soda Lake. In areas the massive to thinly bedded limestone, including Limestone Hill, are exposed on the surface of the mountains (Figure 2) (Grose 1959; Glazner et al. 2002; Harvey and Wells 2003; Michner 1984). Active alluvial fans occur between the mountains and the lakebed (Harvey and Wells 2003).

Between Soda Mountain and Limestone Hill, alluvial deposits consist of sand and gravel (refer to borehole logs for Wells A1, A8, A12, and JW3 in Appendix A). To the east of Limestone Hill, a thin layer of alluvial silty sand overlies sandy silt playa deposits (refer to borehole log for Well MC in Appendix A). MC Spring is located within the alluvium on the eastern side of Limestone Hill. Figure 3 shows the location of monitoring wells and surface water at Zzyzx. Figures 4 and 5 show the geology of the vicinity of Limestone Hill and MC Spring.

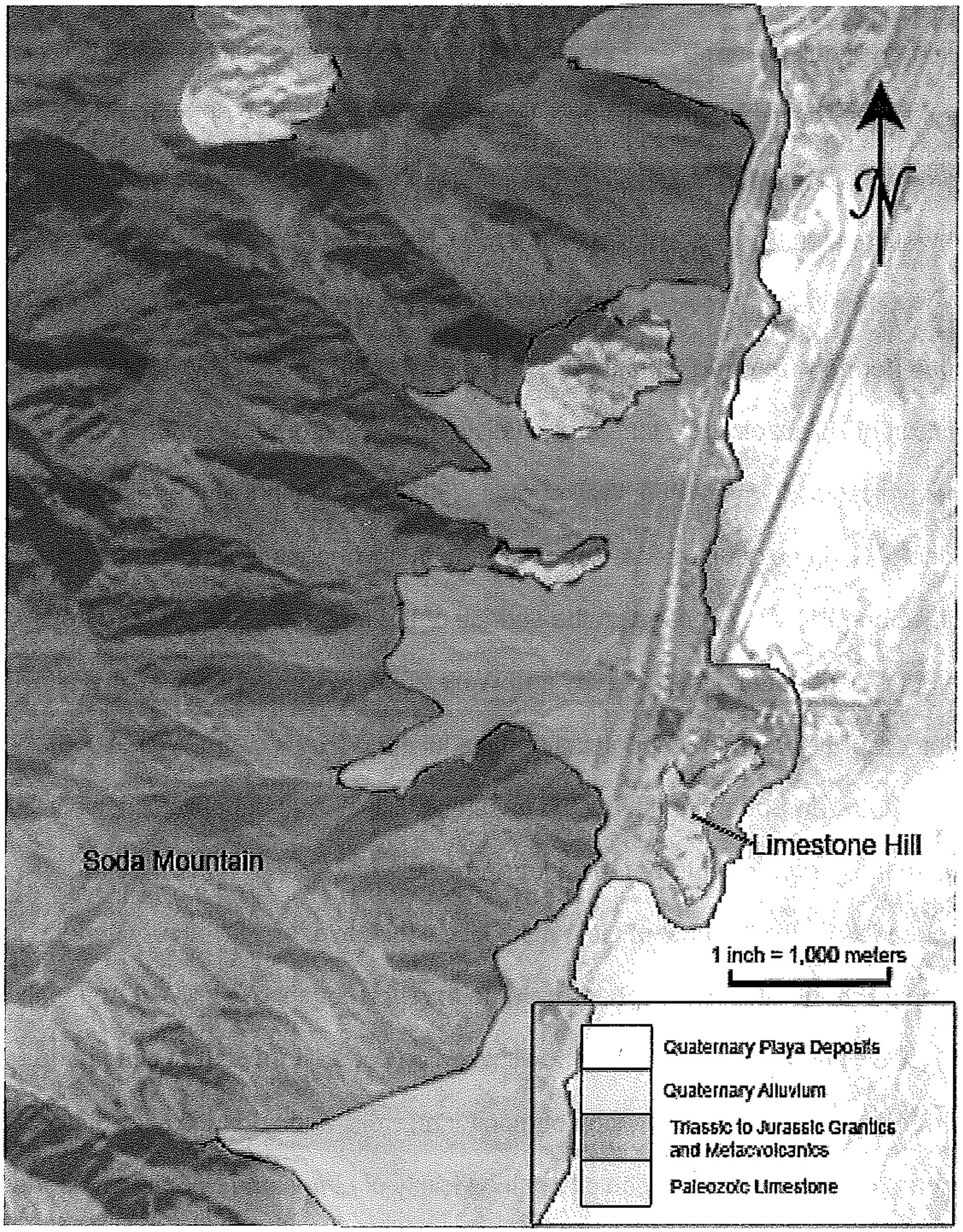


Figure 2. Geology of Southern Soda Mountain. Alluvial deposits separate Soda Mountain and Soda (Dry) Lake playa deposits. Outcrops of limestone are exposed on the surface of the mountain.

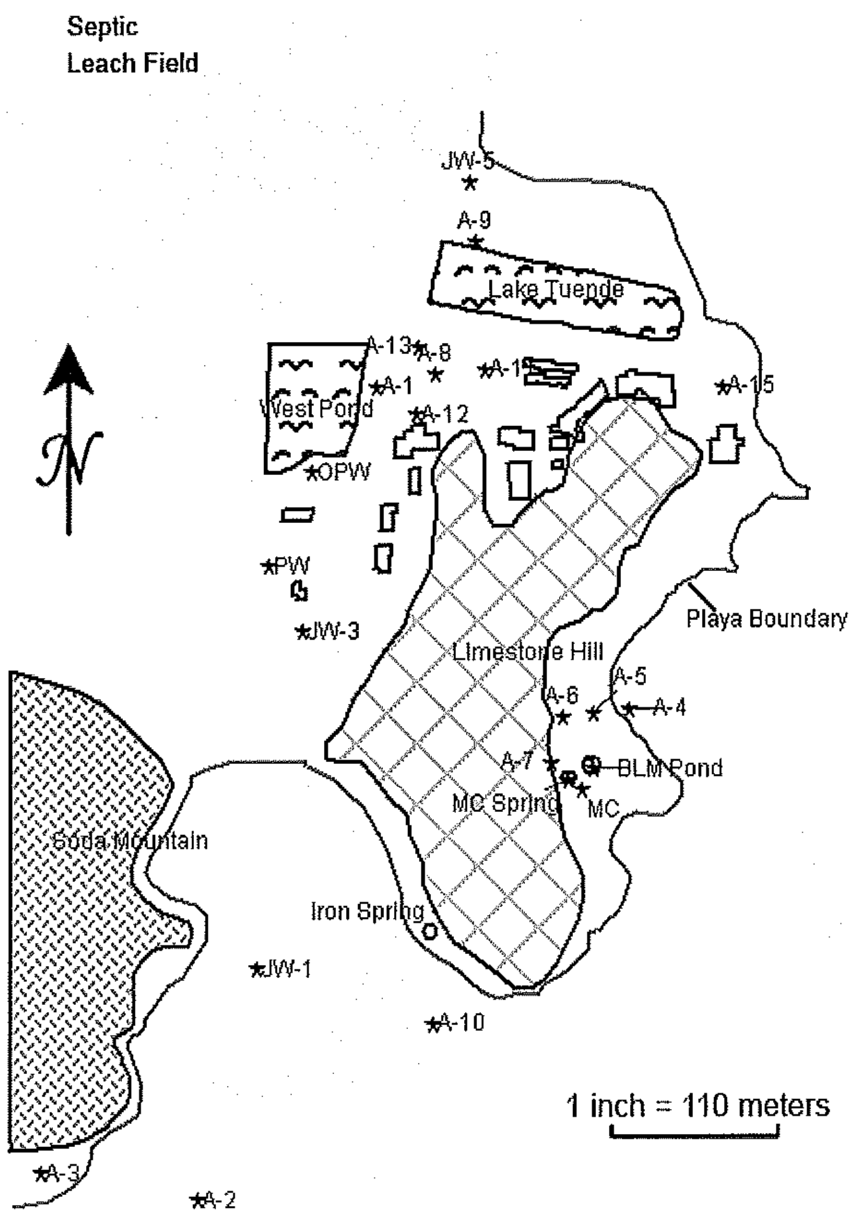


Figure 3. Location of Monitoring Wells and Surface Water at Zzyzx. MC Spring is located on the eastern edge of Limestone Hill. Geology is shown on Figure 4. Borehole logs for Wells A1, A8, A12, and JW3 (Appendix A) show the geology in the alluvial deposits. The borehole log for Well MC shows the contact between alluvial and playa deposits.

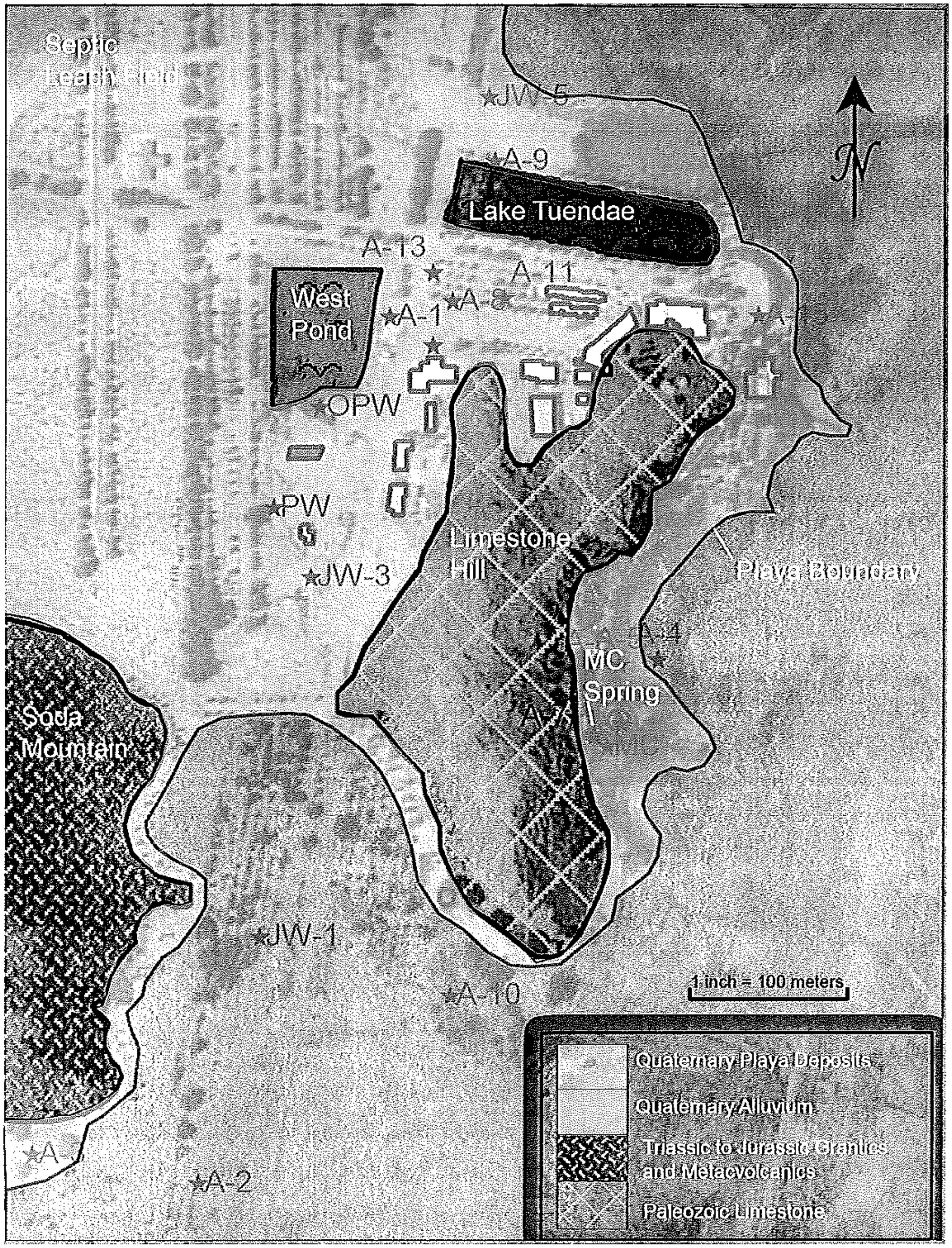


Figure 4. Geology of Zzyzx Desert Studies Center. Limestone Hill is located on the eastern edge of Soda Lake (see Figure 1).

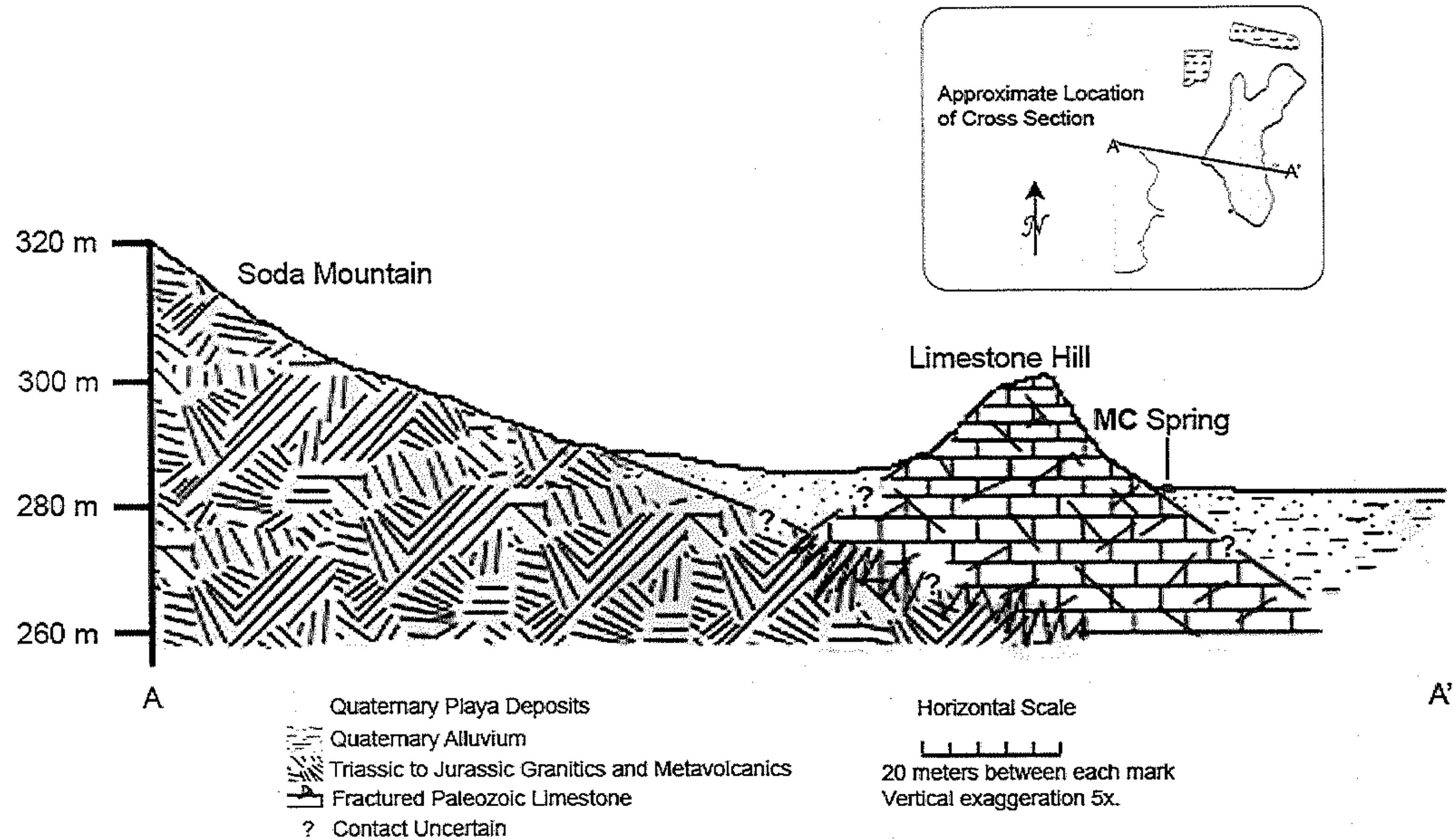


Figure 5. Geologic Cross Section of Zzyzx Desert Studies Center. MC Spring is located in a thin layer of alluvial deposits on the east side of Limestone Hill. Subsurface contacts are uncertain.

Desert Precipitation and Climate

The average annual precipitation at nearby Baker between 1971 and 2007 was 10.62 centimeters (cm) (4.18 inches [in]) (Western Regional Climate Center [WRCC] 2007). The average precipitation reported by National Park Service (1999) between 1931 and 1999 was 8.61 cm (3.39 in). The record high amount of rainfall recorded by Zzyzx personnel was in 1983, with 16.5 cm (6.5 in) of rain. The record low was 1.5 cm (0.58 in) in 2002. During the period that the current study was performed, there were 13.5 cm (5.33 in) of precipitation in 2005. Conversely, 2006 and 2007 were unusually dry; with only 2.4 cm (0.95 in) of rain in 2006 and only 1.9 cm (0.73 in) from January to October 2007 (Desert Studies Center 2007). According to the Drought Monitor website (Drought Monitor 2008), the Zzyzx area has been in conditions of abnormally dry to extreme drought conditions since February 2002 (with the exception of February 2005, which was under normal conditions). The drought conditions were extreme in March and April 2007, and severe most of the rest of the period.

At the weather station in Baker, the average annual mean temperature recorded between 1971 and 2007 was 21.3 degrees Celsius (°C) (70.3 degrees Fahrenheit [°F]) (WRCC 2007). Since 1980, recorded temperatures at Zzyzx have varied from a low of -13 °C (8 °F) in January 1989 and 2007 to 52 °C (125 °F) in July 2007. The average low monthly temperature over a 4-year study period was 9 °C (48 °F) in December and January, and the average high monthly temperature was 34 °C (93 °F) in July (Desert Studies Center 2007).

In the Mojave Desert, much of the precipitation infiltrates only the upper soil zone and is eventually lost to the atmosphere by evapotranspiration (the loss of water to the atmosphere by evaporation, plus transpiration from plant tissue). Zzyzx is located in the California Irrigation Management Irrigation System (CIMIS) Zone 17, valleys in the high desert near Nevada and Arizona (CIMIS 2007), which is characterized by CIMIS as having an average reference evapotranspiration rate of 169 cm (66.5 in) per year.

Groundwater

The Studies Center at Zzyzx is underlain by a shallow alluvial aquifer between Soda Mountain and Limestone Hill. It is presumed that this aquifer is recharged by precipitation through the alluvial fans on the east side of Soda Mountain. Groundwater and surface water flow follow the surface gradient, from Soda Mountain toward Soda Lake, except where Limestone Hill prevents direct flow to the playa in the vicinity of the Studies Center. Bilhorn and Feldmeth (1985) reported elevations in the water supply well, located in the alluvial aquifer, and of MC Spring to be 1.8 to 3 m (6 to 10 ft) above the elevation of the water table in the playa aquifer.

Groundwater in the Soda Lake playa flows northward toward Silver Lake. The playa aquifer receives drainage from Kelso Valley and the Mojave River and is also fed by percolation of precipitation in the basin (Thompson 1929; Dickey et al. 1979). However, only an estimated five percent of the average 10.62 cm

(4.18 in) of rainfall described above infiltrates to the groundwater (Hydrologic Engineering Section [HES] 1985).

Surface Water

Several naturally occurring and man-made bodies of water are located at Zzyzx. Figure 3 shows the locations of MC Spring, BLM Pond, Iron Spring, Lake Tuendae, and West Pond.

MC Spring is the only known location where Mohave tui chub occur naturally (Woo and Hughson 2004). It is an oval-shaped pond exposed on the eastern side of Limestone Hill and has a width of approximately 4 to 5 m (13 to 16 ft) and a depth of approximately 2 m (6.5 ft). The approximate volume of the pond is 31.41 cubic meters (m^3) (8,300 gallons [gal]). The bottom of the spring consists of playa sediments covered in a layer of anaerobic, partly organic mud and aeolian (wind-blown) sediments. Some rocky portions of the bottom may be buried limestone of the nearby hill (Figure 6). MC Spring is modified from its natural state. Records show that the pool has been deepened and enlarged (Bilhorn and Feldmeth 1985). The Zzyzx staff removes vegetation approximately every year to maintain the size of the pool (Fulton personal communication; Woo and Hughson 2004). The water level in MC Spring was constant throughout the study period. The spring is surrounded by vegetation, which is apparently being fed by discharge from the spring as discussed in Chapter 4.

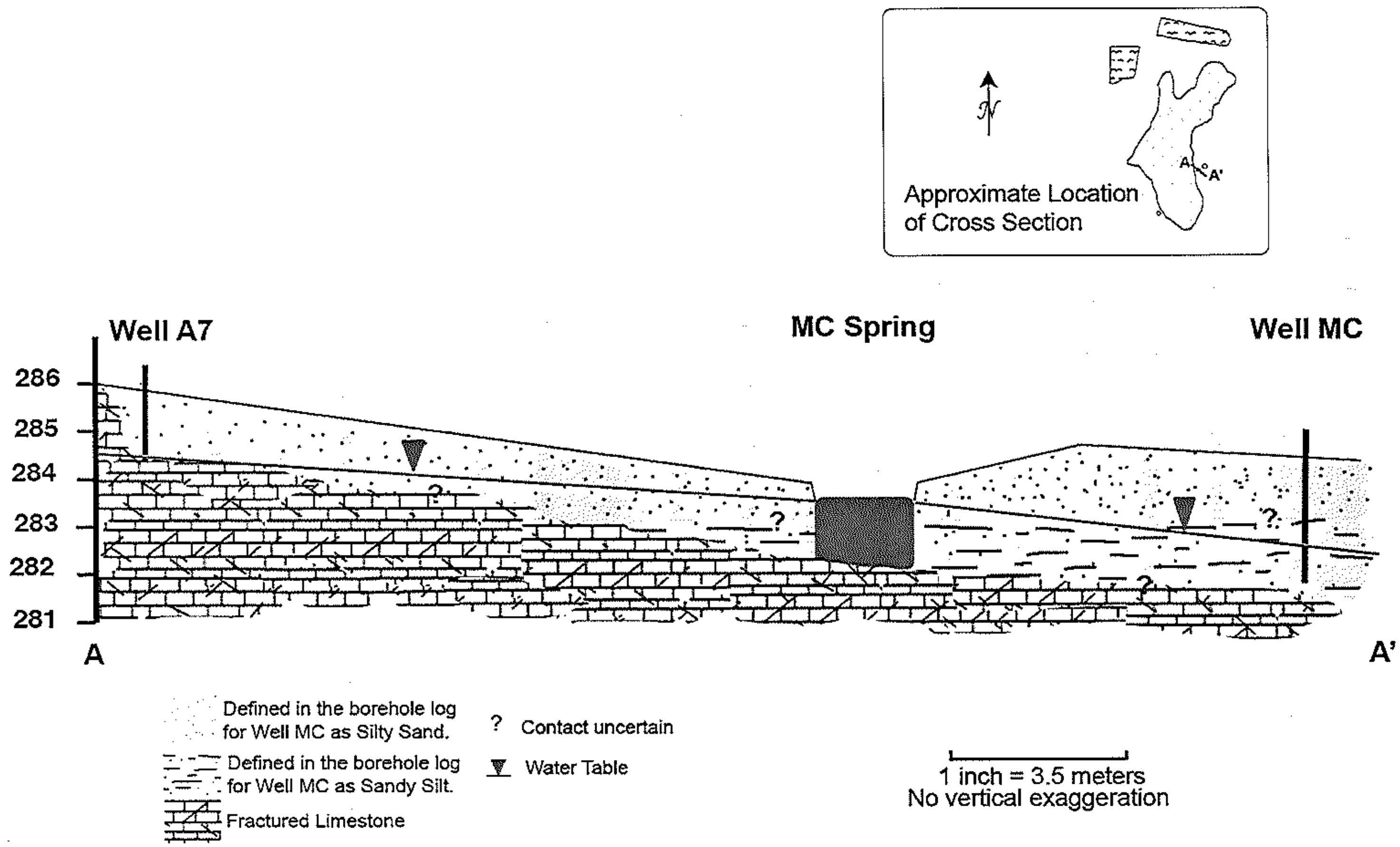
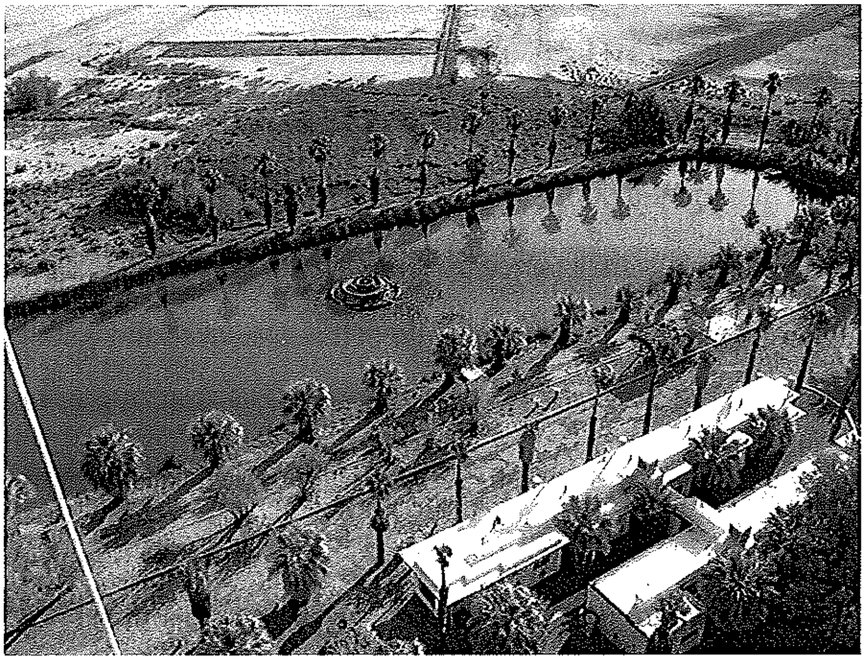


Figure 6. Hydrogeologic Model of MC Spring. Conceptual cross section shows the relationships between Well A7, MC Spring, and Well MC. Subsurface contacts are uncertain.

BLM Pond was installed by the Bureau of Land Management (BLM) some time between 1975 and 1985 7.5 m (25 ft) northeast of the eastern edge of MC Spring. In 1985, the pond was approximately 10 m (30 ft) in diameter; however, the amount of water in the pond is not constant as it is in MC Spring. In April 1985 the volume of BLM Pond was reported as 76.5 m^3 (20,200 gal) and in June of the same year, the water level elevation had decreased by about 1 m (3.5 ft) and the volume had decreased to only 28.3 m^3 (7,500 gal) (Bilhorn and Feldmeth 1985). The pond flows out onto the playa during wet periods. After 1985, BLM Pond was partially backfilled to a depth (when full) of approximately 2 m (6 ft) by Zzyzx personnel. The bottom of the pond originally exposed clayey playa sediments (Bilhorn and Feldmeth 1985) but now is partially filled with materials that were removed during excavation (Fulton personal communication).

At the southwestern corner of Limestone Hill, Iron Spring is identifiable by a growth of large *Tamarix* trees, *Typha* (cattails), and *Anemopsis* (yerba mansa); however, there is currently very little surface water exposed. Bilhorn and Feldmeth (1985) also describe a spring at the south tip of Limestone Hill that "shows a broad area of moisture darkened soil." This area is visible from the ground and from aerial photographs, and evidence of previous marsh vegetation (*Typha*, for example) can be found.

To the north of Limestone Hill, man-made Lake Tuendae also provides a habitat for the Mohave tui chub. The rectangular lake was excavated by Curtis Springer in the early 1950s (Hughson and Woo 2004). The lake measures approximately 150 m by 40 m (490 ft by 130 ft). The bottom of the lake is mud and sand (Fulton personal communication). Discharge from the lake appears to be feeding the wetland area on the northern edge of the lake (Figure 7). The water level in the lake is artificially maintained by the pumping of groundwater from the alluvial aquifer to a fountain near the center of the lake when the water evaporates or percolates into the surrounding ground to approximately 0.6 to 1 m (2 to 3 ft) below the optimal level (Dirling 1997, Fulton personal communication). Archbold (1984) reported maximum depths of 1.3 m (4.3 ft) on the eastern end and 1.6 m (5.4 ft) on the western end, and calculated the average depth to be 1 m (3.1 ft). During a dredging event in 1985 a dam was constructed across the middle of the lake. The western half of the lake could not be completely emptied because of seepage into the lake from the playa aquifer below (Bilhorn and Feldmeth 1985). After the dredging, Bilhorn and Feldmeth reported a maximum depth of 1 m (3.3 ft) in the western end of the lake, and estimated the volume of the lake as 2,240 m^3 (592,000 gal). In 1990 the BLM dredged the eastern end of the lake to a depth of 1 to 2 m (3 to 6 ft). The National Park Service dredged the western end in 2001 to a depth of 2 m (6 ft). The dredging was performed to increase the surface to volume ratio in order to decrease temperature swings and evaporation, to provide an optimal fish habitat (Fulton personal communication).



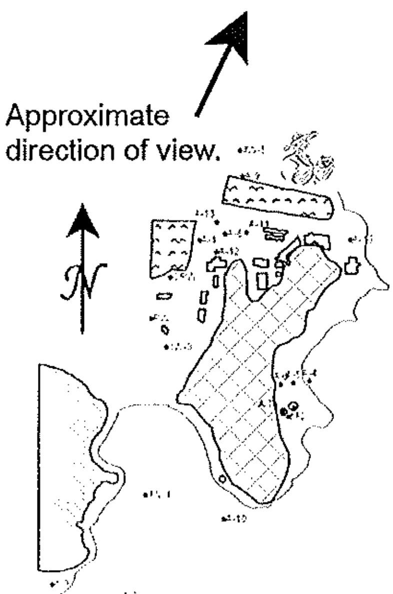


Figure 7. Vegetation on the North Side of Lake Tuendae. Thick vegetation grows here in response to water percolating from the unlined surface of Lake Tuendae. *Top*, taken with blimp-mounted camera by Richard Laton; *bottom*, taken from the ground at the north side of Lake Tuendae.

West Pond was originally excavated by the Tonopah and Tidewater Railroad in 1907 as a borrow pit to provide gravel during construction of the railroad. Curtis Springer likely expanded this pond during his time at Zzyzx. In 1985, the pond had an average depth of 0.3 to 0.45 m (1 to 1.5 ft) and a volume of approximately 2,500 m^3 (660,000 gal) (Bilhorn and Feldmeth 1985). In the late 1980s the BLM expanded the pond to the current shape and depth, as well as forming the islands (Fulton personal communication). This pond is cut into the alluvial aquifer and the water level is not controlled, as is the water level at Lake Tuendae. Archbold (1994) measured depths in West Pond of between 0.03 and 1.9 m (0.3 to 6.1 ft) with an average depth of approximately 1 m (3.4 ft). The bottom of West Pond consists of sandy silt and gravel capped by organic mud and aeolian silt (Fulton personal communication). Between 1981 and 1985, the Mohave chub living in West Pond all died. The suspected cause was an increase in pH and ammonia content, and decreased dissolved oxygen (Dirling 1997). The water in this small lake has a green appearance and often has a sulfurous odor.

CHAPTER 2

PREVIOUS WORK AND DATA GAPS

Although much work has been done in the Mojave Desert, the southern Soda Mountains and the Zzyzx area have not been extensively studied. Reports of the geology, hydrogeology, and geomorphology of Soda Lake and the eastern Soda Mountains (Brown et al. 1990; Butler 1984; Dickey et al. 1979; Enzel et al. 1992; Foster 1984; Grose 1959; Harvey and Wells 2003; HES 1985; Moyle 1967; Muessig et al. 1957; Thompson 1929; Walker and Wardlaw 1989; Wells et al. 2003) were reviewed. These reports are summarized in the Geologic Setting section in Chapter 1.

Thompson (1929) studied the area that was, in his time, called Soda Springs, as part of a report on the water supply potential and basic chemistry of springs throughout the Mojave Desert. He collected samples from a spring and a well at Soda Springs in December 1919. Based on observations of water chemistry at the springs east of Limestone Hill, Thompson noted that the chemical makeup of the water suggested possible sources both through the small limestone outcrop and from the playa.

Michner (1984) and Bilhorn and Feldmeth (1985) also analyzed the chemistry of the groundwater and surface water at Zzyzx. Both reports concluded that the source of Soda Springs was the playa aquifer, which is fed by the Mojave River. Conversely, Foster (1984) concluded that Soda Springs were not directly connected to the playa aquifer but rather occur as a result of artesian pressure created by the very high Soda Mountains from several hundred feet below the ground surface. Bilhorn and Feldmeth compared the deuterium content in samples collected at the Zzyzx supply well (in the alluvial aquifer) with regional rainwater samples and determined that the source of water in the alluvial aquifer to be the San Bernardino Mountains, rather than local rainfall runoff from Soda Mountain.

Archbold (1994) reported results of sampling in 1994 at the newly-installed supply (pumping) well (Well PW), MC Spring, West Pond, and Lake Tuendae and concluded that MC Spring was fed through a fracture system in Limestone Hill. Samples were collected by the Mojave National Preserve from Well PW in May 1998 for general chemistry analysis.

Thompson (1929) suggested that the temperature of the water, between 23 and 26 °C (73.5 and 78.5 °F), was 5 °C (10 °F) above the "probable mean annual temperature of the region" and suggested a source deeper than the fractured limestone. Foster (1984) attributed the water temperature of 24 °C (75 °F) in the springs to deep residence of the source water. Bilhorn and Feldmeth (1985) likewise reported water temperature in the spring of approximately 24 °C (75 °F); however, they suggested that rather than the deep source suggested by Foster, the temperatures approximated seasonal average air temperatures.

Students of the Department of Geological Sciences at CSU Fullerton are among the main students to visit Zzyzx to learn a variety of geologic and hydrologic field analysis techniques. Numerous CSU Fullerton class projects have been conducted on the hydrology and hydrogeology of Zzyzx under the leadership of Dr. Prem K. Saint. Most of these studies were intended as learning tools for specific undergraduate coursework, or as undergraduate or graduate research projects. Students used the data they gathered to complete a specific class project or task. Students working toward their Bachelors or Masters degrees have conducted further studies. For example, Brown (1997) studied the groundwater seeps along the edge of the lakebed at the base of the southern Soda Mountains. Projects reported by Archbold (1994) and Dirling (1997) focused on Mohave tui chub habitat restoration. These reports did not attempt to determine the source of groundwater recharge.

Most of the above-listed studies were accomplished with limited data synthesis or field observations. Because the monitoring wells were installed during several different projects, no comprehensive inventory of the wells was made. Likewise, no survey had been performed to determine the location and elevation of each well. The limited understanding of subsurface geology was based on the available logs of hand-augered boreholes installed under Dr. Saint's leadership.

CHAPTER 3

METHODS

GPS and Map Preparation

The location and elevation of all wells were surveyed with an electronic Total Station and global positioning system (GPS). Various locations within the Zzyzx area were also surveyed. A Trimble Pathfinder Pro-XR Geographic Positioning System was used to determine the location of base stations for the Total Station, other reference locations throughout the area, and wells that were not visible from the Total Station (Wells A3, A10, and A15).

A surface map of the Zzyzx facility including surface features and wells was created using the data from the Total Station and the Pathfinder (Figure 3).

Monitoring Well Inventory

Borehole logs provided by Dr. Saint from previous class and student projects were compiled. Borehole logs are used to interpret subsurface geology. Several attempts have been made to locate the drilling log for Well PW, but to no avail (Fulton personal communication).

A reconnaissance was performed in April 2004 to determine the condition of each well, including whether water was present in the well. Wells that required repair were reported to the site manager, Mr. Rob Fulton.

Groundwater Survey

Groundwater monitoring wells were monitored periodically between March 2005 and June 2006. Beginning in August 2006, monthly monitoring was performed through July 2007. A Solinst 100-foot electrical water-level meter was used to measure the depth of the groundwater from the top of each well casing. Groundwater elevations were determined by subtracting the groundwater level of each well (measured from the top of casing) from the top-of-casing well elevations determined by the GPS survey (as described above). The groundwater elevations from June 2006, September 2006, December 2006, and March 2007 were used to produce groundwater surface maps, illustrating seasonal variations and the change in gradient and direction in the area of the Zzyzx facility.

In addition to water levels, the groundwater temperature, negative logarithm of the hydrogen ion concentration (pH), electroconductivity (EC), and total dissolved solids (TDS) were recorded in each well. From March 2006 through November 2006, a Hanna Model HI 9913000 pH/EC/TDS/temperature waterproof meter was used to measure the temperature (in degrees Fahrenheit [°F]), pH, EC (in microsiemens per centimeter (μS/cm), and TDS (in parts per million [ppm]). Beginning in December 2006, a Hanna DiST6 HI98312 EC/TDS/temperature waterproof meter was used to measure the temperature (in degrees Celsius [°C]), EC (in millisiemens per centimeter [mS/cm]), and TDS (in parts per thousand [ppt]). The Hanna 9913000 was used to measure pH throughout the monitoring period.

Precipitation was compared to groundwater elevations and quality to determine variations between the cold, wet seasons and the hot, dry seasons. These comparisons were also used to better define the water budget of the area.

General ion chemistry, analyzed in March 2005 at CSU Los Angeles, was compared to the field-monitored groundwater quality at several monitoring wells and Well PW. Chemistry data were useful in determining flow paths of groundwater.

Surface Water Survey

Surface water in MC Spring, Lake Tuendae, and West Pond was monitored periodically between March 2005 and June 2006. Beginning in August 2006, monthly monitoring was performed through July 2007. Temperature, pH, EC, and TDS were recorded as described above using a Hanna Model HI 9913000 pH/EC/TDS/temperature waterproof meter, with a limit in EC of 4,000 µS/cm (4 mS/cm) from June 2006 through November 2006. Beginning in December 2006, a Hanna DiST HI98312 EC/TDS/temperature waterproof meter, which can measure EC up to 20 mS/cm, was used. The Hanna 9913000 was used to measure the pH throughout the monitoring period. These water quality parameters were also recorded at Iron Spring in April 2007.

Although there is a gauge in MC Spring, the gauge is not scaled. Photographs (Figure 8) were taken when possible of the gauge to compare the

Figure 8. Measuring Gauge in MC Spring. The gauge is circled in each photograph. Note that although the gauge has painted markings, the markings are not scaled. Water level does not fluctuate seasonally. *Top left*, March 2006. Spring is overgrown; *top right*, May 2007; *bottom left*, July 2007; *bottom right*, November 2006.

relative water level of the spring. In March 2006, MC Spring was overgrown with vegetation and the rod is difficult to see in the photograph. The level of BLM Pond was monitored by observation only. West Pond has a scaled gauge; readings were recorded periodically through the monitoring period. The level of Lake Tuendae is maintained by pumping; therefore, levels were not recorded.

A data logger in Lake Tuendae monitored temperature, DO, pH, and EC. The data downloaded from the logger between November 2003 and June 2004 were provided by Mr. Rob Fulton of the Desert Studied Center.

General ion chemistry analyzed at CSU Los Angeles was compared to the field-monitored water quality at MC Spring. Relationships in water quality of the spring and of groundwater were evaluated.

Resistivity Survey

An electrical resistivity survey was performed in January 2007 to explore the shallow subsurface. The subsurface was not well understood prior to the survey, other than the alluviual sediments that were logged during hand-augering of the groundwater monitoring wells. The subsurface geology and hydrogeology determined by this survey was used to prepare a hydrogeologic model for the site.

An Advanced Geosciences, Inc. SuperSting R8 Induced Polarization (IP) eight-channel automatic multi-electrode system with a 200-watt transmitter powered by two 12-volt vehicle batteries was used to perform the survey. The line was acquired across Zzyzx Road south of Limestone Hill. Sixty-four electrodes (stainless steel stakes) were hammered into the ground at seven-meter intervals. The electrodes were connected via a takeout cable to the transmitter/control box and a switch box, which were placed between electrodes 32 and 33. The cables were checked to be sure of a secure connection, and to be sure no portion of the cable lay in a loop on itself. Contact resistance, which is inversely related to the quality of electrode-to-ground coupling, was high due to the very dry ground. Therefore, water was added to the soil to decrease contact resistance. Up to a gallon of local groundwater was added to some electrodes; the salts in the water effectively decreased contact resistance. After the entire length of the cable was attached (and water added as necessary), a test was run to be sure a signal was being received from each electrode.

Once a good connection to each electrode was confirmed, a current was applied between two electrodes by the transmitter, and the voltage (potential) between two other electrodes was recorded by the receiver. Apparent resistivity, a weighted average of resistivity over a volume of earth, is computed from the measured voltage. Different pairs of electrodes were selected sequentially by the switch box and current and potential electrodes; increasing electrode separation corresponds in general to increasing depth. Locations of current and potential electrodes were systematically varied along the line to yield apparent resistivity values as a function of position along the line (midpoint of the dipoles) and depth (calculated from dipole length and separation).

The current transmitted, voltage received, and cycle information recorded by the SuperSting were downloaded to a computer. The resulting files were processed by EarthImager software.

Fracture Survey

In January 2007 the fracture orientations of Limestone Hill were surveyed. The fracture survey was performed to help build the hydrogeologic model and to assist in pinpointing potential areas of recharge. Four survey stations (Stations 1, 4, 5 and 6) were established. At each station, at least 16 and up to 64 measurements were recorded. The orientations of intrusive trends were also recorded in two locations (Stations 2 and 3). The fracture orientations were plotted on a rose diagram using Rockworks 2002 to determine the predominant orientation of fractures in the limestone.

Vegetation Survey

The vegetation at Zzyzx was mapped in April and May 2007. Vegetation patterns are useful, where well coverage is insufficient, in estimating the depth to groundwater. Meinzer (1927) describes plants that indicate the presence of groundwater and defines the tolerance of certain plants (halophytes) to saline or alkaline conditions common in the Mojave Desert. Additionally, the Desert Studies Center provides a list of plants found at Zzyzx (Desert Studies Center 2007).

Synthesis of Previous Aquifer Test Results

In addition to direct observation and monitoring, synthesis of previously reported data was performed. Data recorded during several aquifer tests performed under the direction of Dr. Prem Saint were compared. The aquifer test data calculated during these studies provided data on the physical properties of the underlying aquifer between Limestone Hill and the southern extent of Soda Mountain. Previous CSU Fullerton student reports on the hydrogeology of the area include Archbold (1994), Brown (1995), Dirling (1995), and Gardiner (1996). Additional aquifer test data reported by Bilhorn and Feldmeth (1985) were also reviewed. Values reported for hydraulic conductivity, transmissivity, storativity, and discharge were synthesized to determine the radius of influence of Well PW (see Figure 3 for well location) and used in producing the hydrogeologic model.

Water Budget

Water budgets for Lake Tuendae and for MC Spring were calculated with the equation described in Fetter (1994): Inflow = Outflow +/- Change in Storage. Inflow at Zzyzx includes precipitation and recirculation of water used by the facility. Outflow includes evapotranspiration (based on pumping data and vegetation distribution); consumption by desert studies visitors and residents; and groundwater seepage. Change in storage includes variations in surface water and groundwater. Values for the calculations were determined by surface water and groundwater well monitoring, comparing rainfall events to groundwater and surface water changes, acquiring information about pumping volumes from

Zzyzx, vegetation mapping, studies of the geology of the area, and synthesizing previous aquifer test data.

Although CIMIS (2007) characterizes the zone including Zzyzx as having an average reference evapotranspiration rate of 169 cm (66.5 in) per year, a more representative rate was determined by direct observation at Zzyzx. Zxyzx is a closed system, in which water does not enter or leave the area except as listed above. Therefore, by including the average annual precipitation recorded in the area (inflow) and the volume of water pumped into Lake Tuendae to maintain its level for a one-year period (outflow), and by the observation that the pumping prevents variations in the elevation of the surface water in the lake (no change in storage), a water budget for Lake Tuendae was calculated with a high degree of confidence. Likewise, the calculated evapotranspiration rate for Lake Tuendae was used to calculate a water budget for the area influenced by MC Spring.

CHAPTER 4

RESULTS

Zzyzx Map

Figure 3 shows the Zzyzx study site including Limestone Hill and the edge of the southern extent of Soda Mountain, surface water features, the playa boundary, groundwater monitoring well locations, and the Studies Center buildings.

Monitoring Well Inventory

Because the wells at Zzyzx were installed in boreholes that were drilled using hand-augered boreholes, none of the boreholes were advanced into bedrock or limestone. Sediments with varying degrees of sand, silt, and clay are the only subsurface geology reported in the logs. The logs do not state whether the total depth of the wells was determined by contact with groundwater or by auger refusal (which could indicate contact with gravel, bedrock, or limestone). Because of this uncertainty, the borehole logs were generally not used in this study to make inferences regarding subsurface geology. The available borehole logs are presented in Appendix A.

Upon inspection in April 2004, many wells were found without caps. The wells were capped to prevent excess evaporation as well as to prevent dilution from precipitation entering the well. Proper well caps were placed on all but one well. Well JW3 has an unusual outer diameter and a cap was not found that would fit upon the top of the casing. Various methods of capping the well were employed, including a nitrile glove and a rinsed drink bottle. The drink bottle proved to be the most resistant to the harsh sun and heat conditions. The above-ground portion of the casing of Well A15 had been broken and repaired prior to this inspection. No properly-fitting cap was installed on this well; the cap rests on the top of the casing.

In June 2006, the amount of stick-up of the casing above the concrete pad or bare ground was measured. The top of casing heights are between 0.03 and 0.7 m (0.1 and 2.3 ft) above the ground or concrete pad surface. A photograph of each well is presented in Appendix B.

Water Table Elevations

It is important to note that 2006 and 2007 were abnormally dry years. As presented in Chapter 1, in 2006 only 2.4 cm (0.95 in) of rain fell at Zzyzx and in 2007 (through September) only 1.9 cm (0.73 in) of precipitation were received. Because of the sparse precipitation in 2006-2007, it is difficult to draw any conclusions about groundwater elevations with respect to precipitation. The minimal amount of precipitation during this time likely evaporated, or perhaps infiltrated only the upper soil layer.

The average water table in a majority of the wells is between 1 and 1.5 m (3 and 5 ft) below the ground surface. Well JW5 behaves as an artesian well; the water level fluctuated from approximately 0.3 to 0.5 m (1 to 1.5 ft) below the top of casing, but was always above ground surface. The total depth of Well JW5 is 5.3 m (17.3 ft), which is among the deepest of the monitoring wells. Only Well OPW is deeper (6.7 m [22 ft]).

The groundwater levels in all of the monitoring wells follow similar patterns, with more shallow water levels in most wells occurring in March 2005, March 2006, and March 2007 and deeper water levels in August 2005 and August 2006 (Figure 9). In contour maps of groundwater elevations for September 2006, December 2006, March 2007, and June 2007 (Figure 10), wells that were not dry (many wells become dry in the warmer months and were not used in the contouring) show a pattern of higher elevation to the southwest, at the base of the southern extent of Soda Mountain, and to the northwest, also from the direction of the Soda Mountains. In general, the alluvial aquifer wells have a water table elevation higher than the playa aquifer wells. The higher elevation continues through the fracture zone in the southern portion of Limestone Hill; the elevation of the surface of MC Spring is very similar to the elevation in wells in the alluvial aquifer. Elevations are 1 to 2 m (3 to 6 ft) lower toward the east and southeast, in the direction of the playa. Except in December 2006, the lowest elevations were measured in wells east of Limestone Hill. In December 2006 the lowest elevation was at Well A9, north of Lake Tuendae. Elevations were lowest overall (of the 4 months plotted) in September 2006, which is near the end of the particularly rainy 2005-2006 season as well as near the end of the typically hot

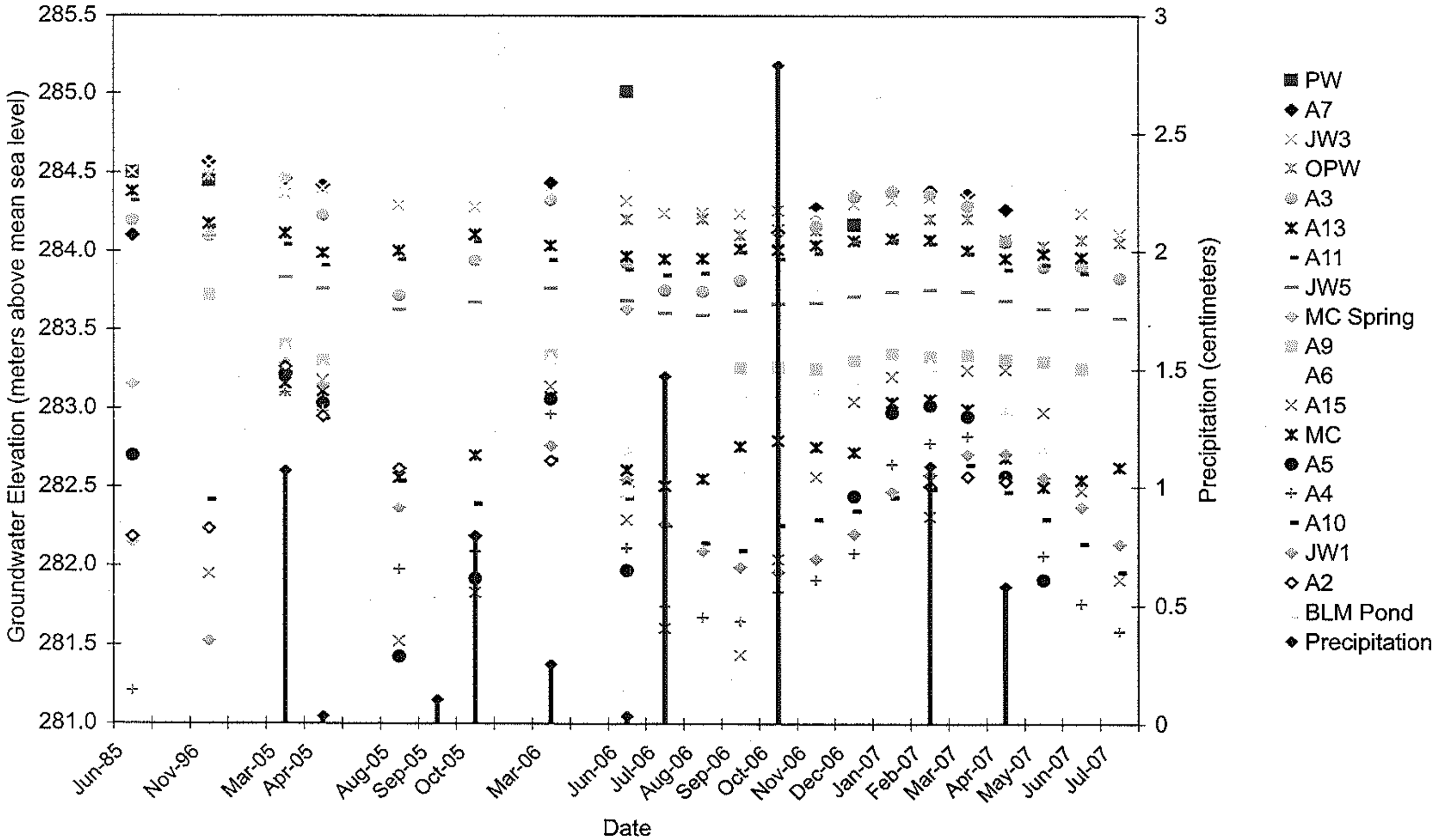


Figure 9. Water Table Fluctuations in Monitoring Wells and MC Spring. Water levels measured in June 1985 (Bilhorn and Feldmeth 1985), November 1996 (Dirling 1997), and from March 2005 through

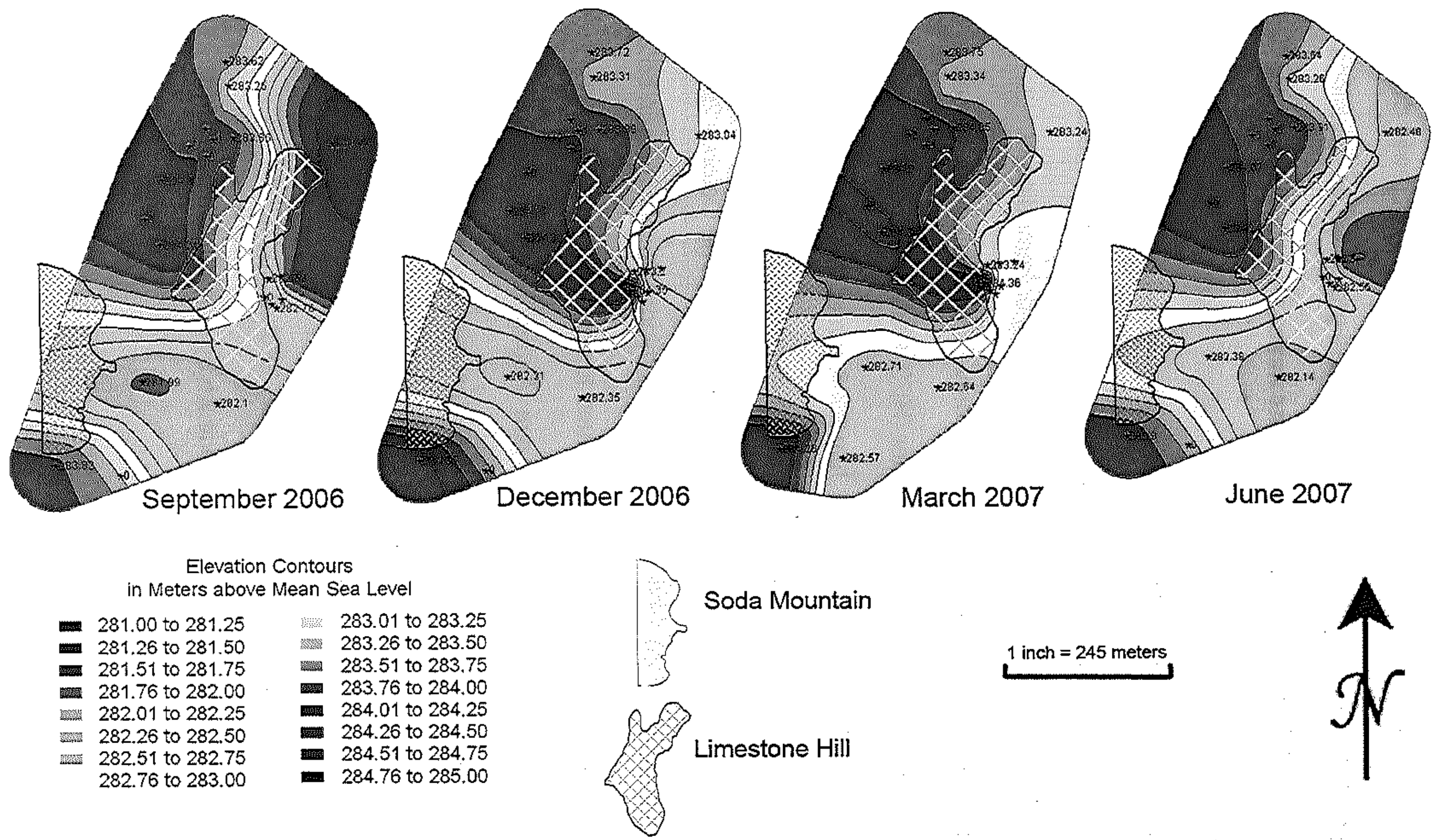


Figure 10. Seasonal Variations in Elevation. Groundwater and surface water elevations in meters above mean sea level at monitoring wells and MC Spring. Wells with an elevation of zero (0) in this figure were dry at the time of measurement, and were not used to determine the contours.

summer. Although this was a wet season, the elevations did not increase directly as a result of precipitation. Likewise, the highest overall groundwater elevations occurred in March 2007, near the end of the colder winter, despite the very dry 2006-2007 precipitation season.

The groundwater level fluctuations appear to be affected by changes in evaporation and evapotranspiration, which fluctuate seasonally with ambient temperatures, rather than by direct local infiltration during or immediately following rainfall events. As stated in Chapter 1, only an estimated five percent of the local rainfall infiltrates to the groundwater (HES 1985). Although Zzyzx received 1.5 cm (0.58 in) of precipitation in July 2006, water levels in general did not increase in the groundwater monitoring wells until October 2006. Likewise, no immediate water level increase occurred after the rather large October 2006 rainfall event of 2.8 cm (1.1 in). Although there were minor rainfall events in both March 2007 and April 2007, water levels continued to drop through July 2007.

In a study conducted with an evaporation pan (Appendix C) between May 1997 and May 1999 at Zzyzx, the average net evaporation potential (accounting for rainfall) was 30.9 cm (12.2 in) in June, 21.9 cm (8.6 in) in September, 7.0 cm (2.8 in) in December, and 10.5 cm (4.1 in) in March. In a typical year, the greatest rainfall in the Mojave region is received in March, August, and September. Evaporation appears to be driven more by ambient temperatures than precipitation.

In general, wells that are located on the playa have groundwater elevations that are approximately 1 m (3 ft) below the elevations of alluvial wells when comparing cool-season elevations. The elevation difference is greater in warm-season elevations; there is a greater elevation fluctuation in playa wells than in alluvial wells (Figure 9). Aside from the seasonal fluctuations, groundwater elevations are relatively similar to water levels reported from June 1985 (Bilhorn and Feldmeth 1985) and November 1996 (Dirling 1997).

The greatest water level fluctuations observed during the current study occurred in Wells A4, A5 (which was dry from July to November 2006 and in June and July 2007), A10, A15, and JW1. These wells are located on the playa (A5 is near the playa boundary) (see playa boundary on Figure 3), suggesting that the playa aquifer water table fluctuates to a greater extent than the alluvial aquifer water table.

Groundwater Quality

Table 1 provides a summary of the groundwater and surface water quality recorded from March 2005 through July 2007. All the recorded data are provided in Appendix D.

In general, the temperatures of the groundwater and surface water monitored ranged from 15 to 32 °C (59 to 90 °F). Of the monitoring wells that were measured (all the wells that were not dry) in September 2006, December 2006, March 2007, and June 2007 (Figure 11), the highest temperature was measured in Well OPW in September 2006. The lowest temperature in that

Table 1. Summary of Groundwater and Surface Water Quality
(Page 1 of 3)

Name	TD	March-06				August-06				September-06				November-06			
		WL	Temp	EC	pH	WL	Temp	EC	pH	WL	Temp	EC	pH	WL	Temp	EC	pH
PW	52.25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A7	5.32	4.78	16.2	>4	6.51	dry	-	-	-	dry	-	-	-	5.3	-	-	-
JW3	10.12	8.19	18.6	>4	6.64	8.6	30.4	>4	6.8	8.62	30.0	>4	7.1	8.62	26.6	>4	6.71
OPW	22	-	-	-	-	5.48	32.7	3.481	7.5	5.81	31.6	3.525	7.6	5.71	25.6	3.465	7.11
A3	6.58	4.08	18.1	3.622	6.36	5.98	31.7	3.140	6.2	5.75	29.1	>4	6.5	4.63	25.7	3.191	6.63
A13	9.74	4.66	15.5	>4	6.37	5.17	33.2	>4	6.5	5.16	31.2	>4	6.9	4.98	26.4	>4	6.46
A12	8.46	5.68	17.2	3.784	6.68	dry	-	-	-	dry	-	-	-	dry	-	-	-
A8	4.78	dry	-	-	-	dry	-	-	-	dry	-	-	-	dry	-	-	-
A11	10.58	4.96	15.7	>4	6.24	5.67	31.6	>4	6.6	5.63	28.2	>4	7.3	5.33	24.9	>4	6.38
JW5	17.32	1.03	15.6	2.980	6.87	1.6	29.2	3.069	6.9	1.51	27.2	3.120	7.7	1.34	20.7	3.027	7.18
MC Spring			17.6	2.995	7.05		25.6	>4	6.9		22.9	3.068	7.3		20.2	2.988	6.85
A9	4.73	4.25	13.1	>4	6.54	dry	-	-	-	4.51	-	-	-	4.53	20.2	>4	6.26
A6	7.99	4.8	16.7	>4	6.25	7.64	31.3	3.625	6.2	7.09	27.3	>4	6.1	5.45	24.0	>4	5.65
A15	11.85	6.12	17.4	>4	5.91	dry	-	-	-	11.71	-	-	-	8.01	25.1	>4	6.15
MC	10.48	4.3	16.1	3.443	6.29	6	25.9	>4	6.1	5.32	24.2	>4	6.4	5.33	21.8	>4	6.31
A5	8.12	2.73	12.7	>4	6.21	dry	-	-	-	dry	-	-	-	dry	-	-	-
A4	13.5	2.67	15.6	>4	6.97	6.9	29.2	>4	7	6.98	28.1	>4	7.1	6.13	25.4	>4	6.86
A10	9.94	4.37	16.1	>4	6.37	6.1	30.0	>4	6.7	6.26	28.0	>4	6.9	5.61	23.8	>4	7.03
JW1	11.96	6.38	17.7	>4	6.19	8.57	29.2	>4	6.2	8.91	27.1	>4	6.3	8.74	25.1	>4	6.24
A2	5.72	4.98	15.5	>4	7.2	dry	-	-	-	dry	-	-	-	dry	-	-	-
Lake Tuende			12.3	>4	7.51		30.1	>4	6.9		23.6	>4	8.4		-	-	-
BLM Pond			12.8	3.315	7		24.3	>4	6.5		19.1	>4	6.8		-	-	-
West Pond			-	-	-		-	3.080	-	40	23.9	>4	8.2	44	-	-	-
Iron Spring			-	-	-		-	-	-		-	-	-		-	-	-

Table 1. Summary of Groundwater and Surface Water Quality
(Page 2 of 3)

Name	TD	December-06				January-07				February-07				March-07			
		WL	Temp	EC	pH	WL	Temp	EC	pH	WL	Temp	EC	pH	WL	Temp	EC	pH
PW	52.25	12.85	19.8	3.25	7.43	-	-	-	-	-	-	-	-	-	-	-	-
A7	5.32	5.05	21.1	7.54	-	4.95	16.2	6.41	6.41	4.95	20.4	5.3	6.82	5.02	-	-	-
JW3	10.12	8.41	22.9	5.16	-	8.33	22.7	5.36	6.87	8.28	23.3	4.94	7.04	8.28	25.1	5.39	6.95
OPW	22	5.4	22.8	3.52	7.11	-	-	-	-	5.48	21.5	3.58	7.05	5.48	24.5	3.41	7.02
A3	6.58	4.01	23.9	5.53	-	3.91	18.8	4.86	6.43	3.96	21.9	4.3	6.78	4.22	24.1	4.49	6.4
A13	9.74	4.87	19.5	15.45	-	4.78	17.8	14.19	6.49	4.74	21.4	12.78	6.49	4.76	24.6	12.2	6.3
A12	8.46	dry	-	-	-	muddy	-	-	-	dry	-	-	-	dry	-	-	-
A8	4.78	muddy	-	-	-	muddy	-	-	-	4.77	22.6	10.77	6.57	4.47	-	-	-
A11	10.58	5.21	19.8	15.18	-	4.96	19.4	13.95	-	4.92	22.5	12.99	6.71	5	23.5	12.94	6.2
JW5	17.32	1.2	18.9	3.22	-	1.11	17.8	3.66	7.26	1.07	17.5	3.071	7.23	1.1	24.7	2.92	7.09
MC Spring			20.1	3.07	-		16.6	3.33	7.14		21.8	3.07	7.35		23.9	2.92	7.09
A9	4.73	4.36	16.4	12.07	-	4.22	14.4	10.62	6.25	4.28	17.8	11.67	6.5	4.25	24.4	8.49	6.61
A6	7.99	5.21	20.0	6.27	-	4.97	NM	5.58	6.39	4.93	20.3	4.48	6.83	5.05	22.6	4.64	6.35
A15	11.85	6.44	22.3	>20	-	5.92	18.5	>20	6.01	8.84	20.4	18.7	6.24	5.78	22.2	11.2	6.41
MC	10.48	5.44	21.7	4.63	-	4.4	15.8	5.01	6.47	4.34	19.9	4.89	6.83	4.55	22.2	3.65	6.52
A5	8.12	4.77	19.0	>20	-	3.02	13.6	16.07	6.76	2.87	17.5	12.75	6.76	3.09	20.3	11.96	6.64
A4	13.5	5.57	20.3	>20	-	3.71	16.5	>20	7	3.27	17.7	>20	7.22	3.13	22.8	>20	7.1
A10	9.94	5.43	22.8	>20	-	5.15	19.1	>20	6.58	4.98	19.8	>20	6.79	4.47	22.7	>20	6.49
JW1	11.96	8.22	23.7	12.54	-	7.34	19.6	13.52	6.37	6.99	21.5	13.81	6.38	6.56	25.1	14.38	6.22
A2	5.72	dry	-	-	-	muddy	-	-	-	5.51	23	>20	6.34	5.31	23.8	>20	7.24
Lake Tuende			14.6	4.29	-		-	-	-		17.9	4.18	7.58		24.1	4.16	7.5
BLM Pond			15.4	3.29	-		12.8	3.47	6.34		16.2	3.23	6.74		20.2	3.6	6.57
West Pond			-	-	-		-	-	-	50	-	-	-	50	25.3	>20	7.98
Iron Spring			-	-	-		-	-	-	-	-	-	-				

Table 1. Summary of Groundwater and Surface Water Quality
(Page 3 of 3)

Name	TD	April-07				May-07				June-07				July-07			
		WL	Temp	EC	pH	WL	Temp	EC	pH	WL	Temp	EC	pH	WL	Temp	EC	pH
PW	52.25	-	-	-	-	-	-	-	-	-	-	-	-		pumping		
A7	5.32	5.34	-	-	-	muddy	-	-	-	muddy	-	-	-	dry	-	-	-
JW3	10.12	9.17	33.8	5.74	6.88	9.41	-	-	-	8.61	29	4.79	6.99	9.03	27.7	5.32	7.45
OPW	22	5.9	28.9	3.25	6.98	6.04	29.9	3.3	7.31	5.91	29.3	3.29	7.54	5.97	29	3.36	8.06
A3	6.58	4.95	32	4.07	6.53	5.48	32.8	4.72	6.75	5.47	29.1	2.54	6.61	5.71	27.3	3.85	7.35
A13	9.74	4.99	31.7	11.87	6.72	5.16	30.1	13.52	6.43	5.07	27.9	14.66	6.54	5.14	29.9	15.45	7.56
A12	8.46	dry	-	-	-	dry	-	-	-	dry	-	-	-	dry	-	-	-
A8	4.78	4.94	-	-	-	dry	-	-	-	dry	-	-	-	dry	-	-	-
A11	10.58	5.22	28.8	12.82	6.38	5.56	29.5	13.29	6.64	5.46	27.2	14.21	6.5	5.63	28.2	13.69	6.94
JW5	17.32	1.29	28.9	2.88	7.21	1.47	30.3	2.88	7.36	1.46	25.5	3.23	7.37	1.66	29.1	3.02	8.05
MC Spring			32	2.9	7.33		30.2	2.82	7.13		25.9	2.98	7.27		25.2	3.19	7.98
A9	4.73	4.34	29.4	6.82	6.74	4.39	-	-	-	4.53	-	-	-	dry	-	-	-
A6	7.99	5.88	29.6	3.91	6.33	6.63	28.9	3.83	6.57	7.49	-	-	-	dry	-	-	-
A15	11.85	5.77	23	9.4	6.61	6.67	27.1	7.15	6.27	8.3	28	8.99	6.44	10.15	27.4	8.62	6.52
MC	10.48	5.56	28.6	3.92	6.59	6.17	25.9	4.23	6.31	6.02	22.4	4.89	6.42	5.76	24.9	7.98	6.51
A5	8.12	4.35	-	10.54	6.92	6.5	23.7	15.58	6.58	dry	-	-	-	dry	-	-	-
A4	13.5	4.02	28.3	>20	7.31	5.62	27.8	>20	7.41	6.61	26.2	>20	7.63	7.19	26.8	>20	8.16
A10	9.94	5.03	29.6	>20	6.65	5.6	28.7	>20	6.6	6.12	28.2	>20	6.86	6.71	25.6	>20	7.07
JW1	11.96	6.55	31.2	14.48	6.28	7.05	29.7	14.75	6.26	7.66	27	14.31	6.4	8.43	26.4	13.46	6.83
A2	5.72	5.41	33.4	>20	7.43	muddy	-	-	-	dry	-	-	-	dry	-	-	-
Lake Tuende			28.5	3.96	7.84		28.8	4.15	8		26.4	4.3	8.47		27.7	4.39	8.91
BLM Pond			WL down				WL very low				-	-	-		-	-	-
West Pond		49	-	-	-		-	-	-	40	-	-	-	38	-	-	-
Iron Spring			29.7	4.95	6.61		-	-	-		-	-	-		-	-	-

Notes:
Lake Tuendae was monitored near the northwest corner of the lake.
Wells A1, JW2, and JW4 were dry throughout the study period.

Units of Measure:
EC millisiemens per centimeter (mS/cm)
Temp degrees Celsius (°C)

Acronyms:
- not measured
EC electroconductivity
pH negative logarithm of the hydrogen ion concentration
TD total depth (measured in feet below top of casing)
Temp temperature
WL water level (measured in feet below top of casing)

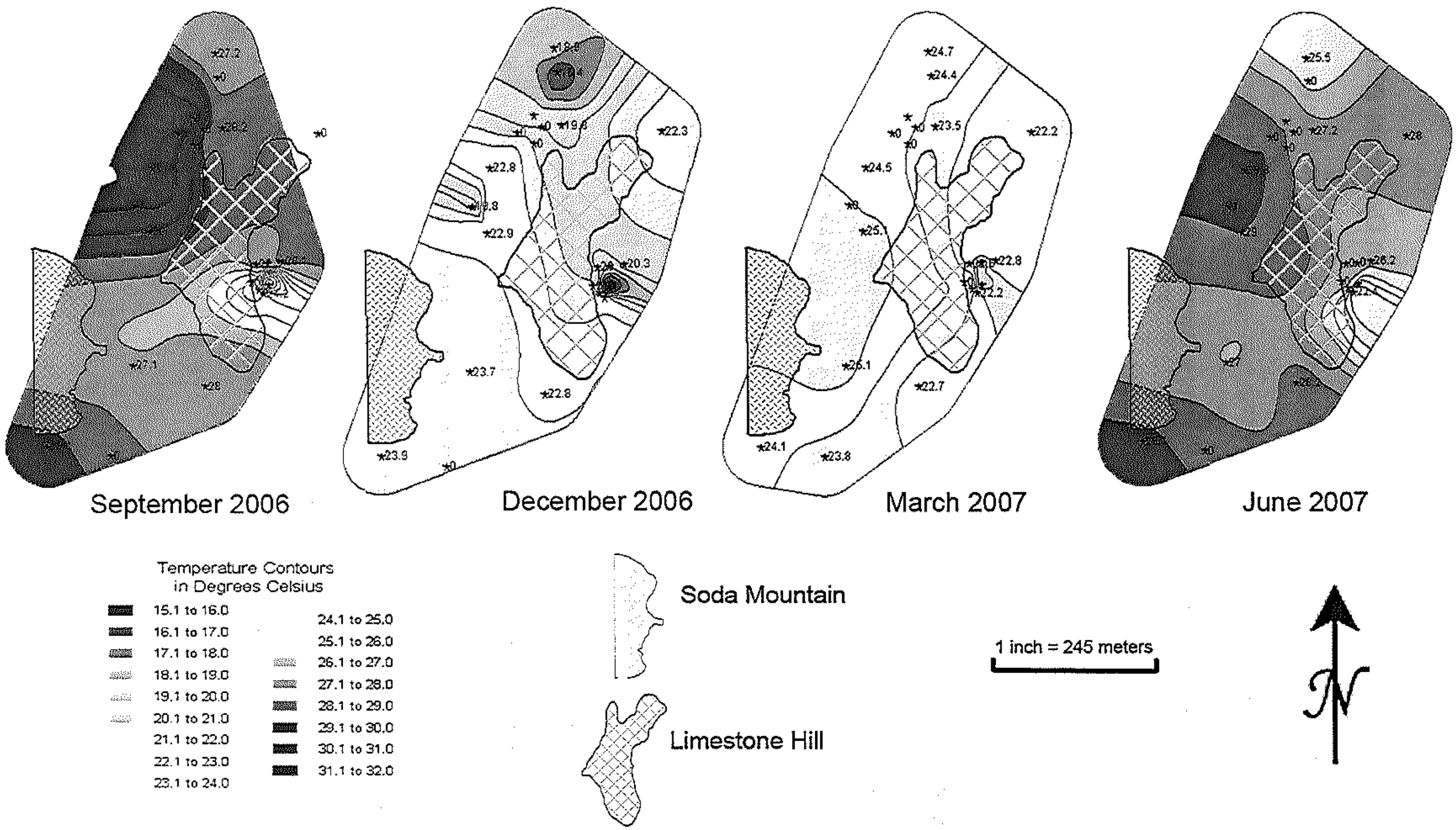


Figure 11. Seasonal Variations in Temperature. Temperature of groundwater in degrees Celsius collected from monitoring wells and surface water in MC Spring. Wells with a temperature of zero (0) in this figure were dry at the time of collection, and were not used to determine the contours.

month (in Well MC) was higher than the highest temperature in December 2006 (in Well A3). The lowest temperature in December 2006 (an in all the months compared) was in Well A9.

Values recorded for EC content (Figure 12) were lowest in wells located toward the western portion of the study area, closest to Soda Mountain, ranging between 2 and 6 mS/cm. Even wells in the northwest, closest to the center's septic leach field (Figure 2), show low EC values. The pattern of relatively low EC values continues through Limestone Hill (Figure 13), where alluvial aquifer water may be traveling through fractures in the hill toward MC Spring. EC values were highest in wells on or near the playa (Wells A2, A4, A5, A10, A15, and JW1), ranging between 10 and 17 mS/cm. The EC values of Wells A4 and A10, located on the playa, were above the range of the instrument (20 mS/cm) throughout the study period. This pattern follows very closely the pattern of groundwater elevations in the measured wells, as discussed in the previous section. EC did not fluctuate greatly between December 2006, March 2007, and June 2007. Varying patterns in contour maps are due to dry wells not being included in contouring, rather than fluctuations in EC values.

No discernable patterns between wells are seen in pH values (Figure 14). In general, pH ranged from approximately 6 to 8 throughout the study period.

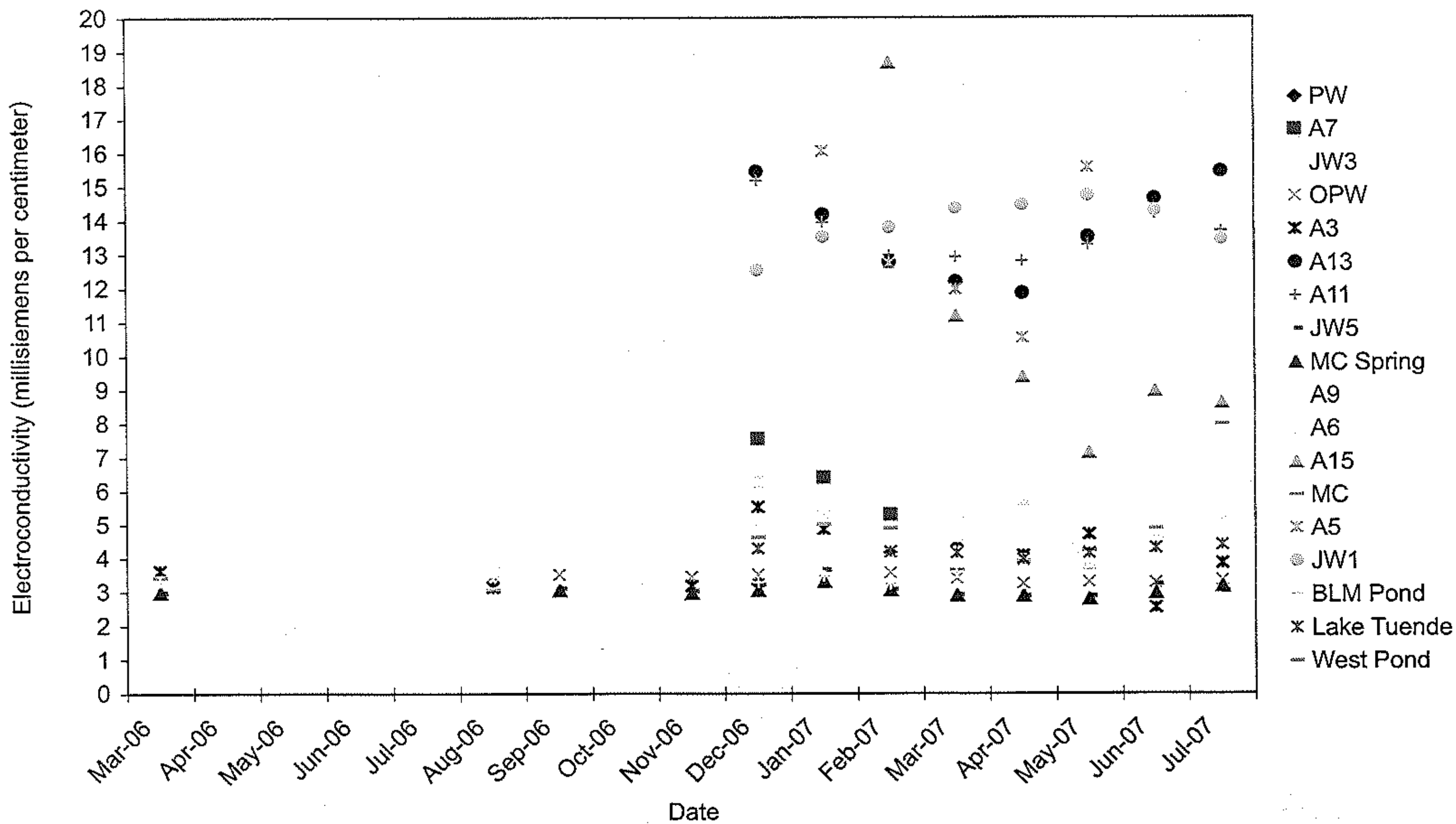


Figure 12. Electroconductivity Fluctuations in Monitoring Wells and MC Spring from March 2006 through July 2007. Values greater than 4 millisiemens per centimeter (mS/cm) through November 2006 and greater than 20 mS/cm beginning December 2006, were beyond the range of the meter and are not included. Wells A1 and A4 had values greater than 20 mS/cm throughout the study period, and are not included.

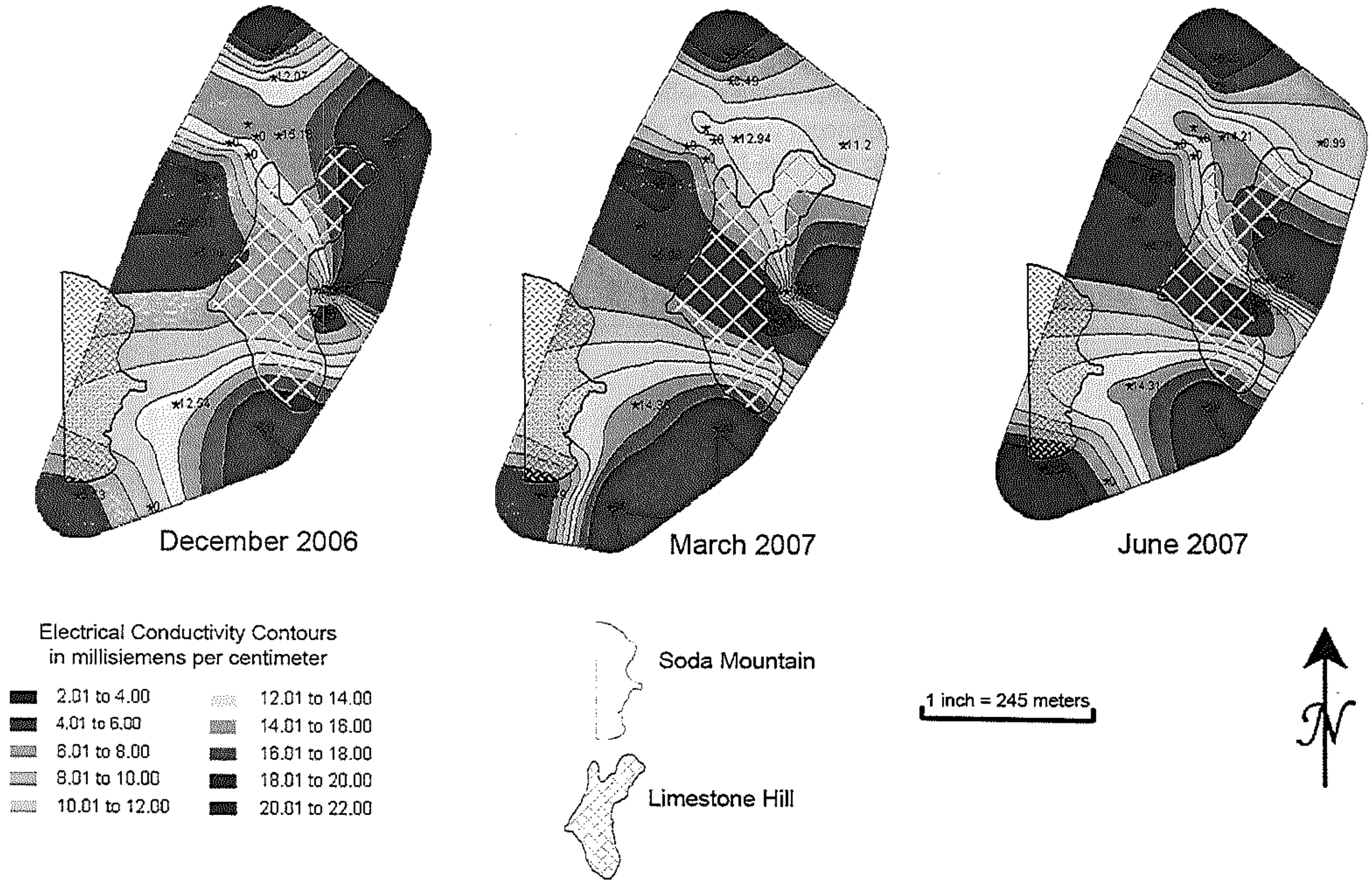


Figure 13. Seasonal Variations in Electroconductivity. Conductivity in millisiemens per centimeter of groundwater collected from monitoring wells and surface water in MC Spring. Wells with an electroconductivity of zero (0) in this figure were dry at the time of collection, and were not used to determine the contours.

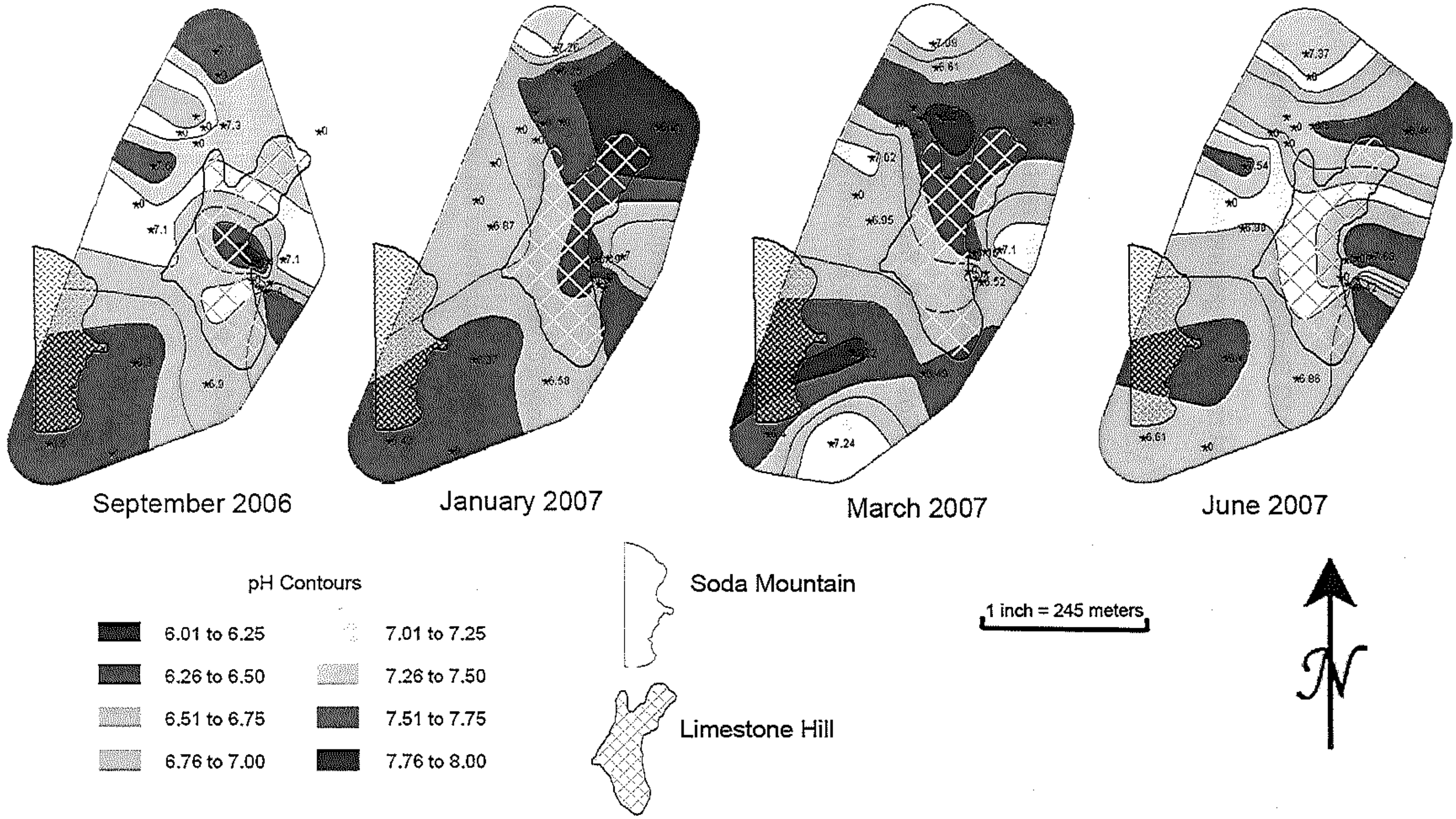


Figure 14. Seasonal Variations in pH. pH of groundwater collected from monitoring wells and surface water in MC Spring. Wells with a pH of zero (0) in this figure were dry at the time of collection, and were not used to determine the contours.

Surface Water Quality

In June 2006, the elevation of the surface of MC Spring was 283.64 m (930.57 ft) above mean sea level (Figure 9). In MC Spring, the temperature was about mid-way between the lowest and highest recorded groundwater temperature in December 2006, March 2007, and June 2007 (refer to Table 1 for values). In September 2006, the temperature of MC Spring was lower than the groundwater temperatures (Figure 11). Contrary to observations recorded in previous reports in which temperature was said to indicated a deep source of water recharging MC Spring (Thompson 1929; Foster 1984), the temperature of MC Spring observed in this study fluctuated in response to, and with relatively similar temperatures to, the ambient temperature as suggested by Bilhorn and Feldmeth (1985). The EC values at MC Spring had a similar range (2 to 6 mS/cm) as Wells JW5 and OPW, both located in the alluvial aquifer (refer to Table 1 and Figure 12). By contrast, the EC in wells located on the playa ranged from 10 to 17 mS/cm. The pattern of relatively low EC values from the alluvial aquifer wells continues through Limestone Hill (Figure 13), where alluvial aquifer water may be traveling through fractures in the hill toward MC Spring. This pattern follows very closely the pattern of groundwater elevations in the measured wells. The pH values at MC Spring were also among the lower values recorded, although no patterns could be discerned for pH in the entire area (Figure 14).

In June 2006, the elevation of the surface of BLM Pond was 282.47 m (926.75 ft) above mean sea level (Figures 9 and 10). Between April and July 2007, BLM Pond became nearly dry. When measured, BLM Pond had among the lowest temperature of all the recorded temperatures (Figure 11); the level in BLM pond was quite low from April to July 2007 and the water was not measured. The EC at BLM pond was slightly higher than that of MC Spring in each monthly measurement collected for both surface water bodies (Figure 12), but lower than wells on or near the playa. The pH at BLM pond measured lower than MC Spring in each month that parameters were recorded (Figure 14).

In April and August 2007, Iron Spring (refer to Figure 3) was a very shallow pool and was nearly hidden in *Typha* (cattails), *Phragmites* (reed grass), and deciduous *Tamarix* (Salt Cedar) trees. Water quality parameters were measured in April 2007. Temperature was 29.7 °C (85.5 °F), EC was 4.95 mS/cm, and pH was 6.61. South of the spring, the ground has a dark quality and there are remnants of cattails. The past presence of cattails indicates that this area at one time had water at the surface. Currently, groundwater is found in Well A10 at approximately 1.2 to 1.5 m (4 to 5 ft) below ground surface (bgs).

Water quality values were recorded during monthly monitoring at Lake Tuendae, although no set location or depth of sampling was chosen. In general the EC of Lake Tuendae ranged slightly higher than that of the alluvial aquifer wells. As described in Chapter 1, Lake Tuende is fed in part by the playa aquifer, and diluted by pumped alluvial aquifer water. Results recorded by a data logger in Lake Tuendae from November 2003 to June 2004 are presented in Appendix C. Temperature, EC, and pH increased throughout this time period. Dissolved oxygen increased through March 2004, then decreased to approximately the same value in June 2004 as it had been in November 2003. Relative to the overall patterns, diurnal fluctuations are very pronounced in the dissolved oxygen and pH values; temperature and EC do not show much diurnal fluctuation.

Water quality parameters were only measured in West Pond in September 2006 and March 2007, in order to avoid contamination of the field instruments. The pH values were higher than the pH of any groundwater or any other surface water measured. The EC was higher than the limit of the Hanna instrument. Although West Pond is located in the area of the alluvial aquifer, the EC value is more closely associated with those in playa aquifer wells. The elevated EC is due to evaporation of water from the pond; which decreases the water quality. Unlike Lake Tuendae, West Pond is not diluted by pumping from the alluvial aquifer.

<u>Ion Chemistry by Laboratory Analysis</u>

Results of laboratory analyses performed on samples collected in 1919, 1994, 1998, and 2005 are summarized in Table 2 and discussed below. Graphs of 2005 anion analysis results are included in Appendix E.

Samples were analyzed in 1919 from a well and a spring at Zzyzx (at that time called Soda Station). The highest cation content found in the samples was sodium (Na) with a result an order of magnitude greater than calcium (Ca),

Table 2. Summary of Laboratory Ion Results for Samples Analyzed in 1919, 1994, 1998, and 2005

	Ca	K	Mg	Na	Cl	F	NO_3	SO_4
1919								
Well	18	see Na	6.3	(+K) 658	688	-	1.0	316
Spring	16	16	5.0	708	736	-	2.2	321
July 1985								
Supply Well	25	16	7	760	765	-	-	18
MC Spring	14	14	6	640	607	-	-	240
Lake Tuende (1982)	25	21	3.2	776	846	10	-	387
West Pond	10	49	5	2,500	2,414	-	-	1,050
June 1994								
Well PW (1989)	39	11	6	89	-	-	5	397
MC Spring	14	13	5	660	690	8.6	5	320
Lake Tuendae	12	15	4	980	1,100	13	<1	450
West Pond	20	72	9	4,200	4,600	51	3	2,000
May 1998								
PW	2.7	11.6	8.1	700	732	8.94	7.1	321

March 2005	Br	Cl	F	NO_2	NO_3	PO_4	SO_4
Well PW	0.7	798.7	9.2	0.8	6.6	0.2	348.5
Well A7	3.1	4,059.7	18.0	3.4	22.9	1.9	2,043.7
Well JW3	1.1	1,348.2	13.2	0.9	2.9	0.4	516.7
Well JW2	2.4	3,013.9	11.7	2.7	0.4	1.4	1,184.8
Well A3	1.3	1,486.5	13.1	1.3	0.0	0.4	701.0
Well A12	1.0	1,315.9	9.0	0.9	26.2	0.4	582.7
MC Spring	0.7	676.6	8.8	0.9	5.5	0.4	308.4
Well A6	1.1	1,339.5	20.5	0.9	0.1	1.1	615.4
Well A15	2.8	3,419.7	17.1	2.0	0.4	4.9	1,596.0
Well MC	0.9	1,061.5	12.0	0.6	0.6	0.5	528.3
Well A5	5.9	7,299.7	10.5	2.3	0.5	6.1	3,865.4
Well A4	13.9	16,742.2	26.6	1.0	8.3	11.5	9,685.3
Well A10	9.4	11,646.6	10.0	0.5	0.8	5.4	4,433.1
Well JW1	10.9	14,170.7	5.9	1.0	1.0	6.1	8,656.2
Well A2	16.0	18,413.5	38.1	1.0	39.8	7.2	6,371.8

Notes:
All results reported in milligrams per liter (mg/L) or the equivalent parts per million (ppm).

Sources:
Thompson 1929 (1919 data)
Bilhorn and Feldmeth 1985 (1985 data)
Archbold 1994 (1994 data)
Mr. Rob Fulton (1998 data)
Dr. Barry Hibbs (2005 data)

magnesium (Mg), and potassium (K). The highest anion was chloride (Cl), with a result two orders of magnitude greater than nitrate (NO_3). Although the exact location of the well that Thompson (1929) sampled is not known, and it is uncertain whether his spring is in the identical location of the current MC Spring, the water quality parameters he reported indicate that both the well and the spring had chemistries similar to the current Well PW (in the alluvial aquifer) and MC Spring, respectively. The exception to this observation is the NO_3 result, which in 1919 was relatively low, more similar to the 2005 results for NO_3 in Well A10 on the playa than in Well PW or MC Spring.

Archbold (1994) reported results of sampling at Well PW in 1989 and at MC Spring, Lake Tuendae, and West Pond in 1994. The highest cation content in each sample was Na; the highest anion content in each sample was Cl (Cl was not reported for Well PW, SO_4 was the predominant anion in that sample).

A sample analyzed from Well PW in May 1998 found a content of Cl twice that of SO_4, and two orders of magnitude greater than fluoride (F) and NO_3. Additionally, the well was analyzed for cations and was found to have a Na content at least an order of magnitude greater than Ca, Mg, or K.

The laboratory analysis performed in selected wells and in MC Spring in March 2005 (Table 2) found the water at Zzyzx to be strongly Cl- and SO_4-rich, with those anions being as much as five orders of magnitude more elevated than bromide (Br), F, NO_3, nitrite (NO_2), and phosphorus (PO_4). The highest total anion content (of the anions listed above) was found in Wells A2, A4, and JW1

(Figure 15). Wells A5 and A10 had lower anion content. Lower still was the anion content of Wells A7, A15, and JW2 (this well was dry during the entire monthly monitoring period). The lowest anion content was found in MC Spring and in Wells A3, A6, A12, JW3, PW, and MC.

Pumping in the Alluvial Aquifer

Well PW is used to provide the center with its water needs. Pumping was monitored from September 2006 through August 2007 (Appendix C). In that time, a total of 10.6 million gal were pumped from the alluvial aquifer. Of this volume, Lake Tuendae received 9.27 million gal; 1.17 million gal were pumped to the reservoir for use in the Studies Center kitchen and bath facilities; and 0.13 million gal were pumped into the pool for use by personnel and visitors during the summer months (the pool received water only during September 2006 and April through August 2007).

Evapotranspiration

Water loss to the atmosphere due to evapotranspiration is a major factor in a desert water budget. The total average annual evapotranspiration reported by CIMIS (2007) is 1.69 m (66.5 in) per year. However, because Zxyzx is a closed system, a more representative rate was calculated based on pumping data recorded at the Studies Center. The calculated evapotranspiration of the 2-acre Lake Tuendae watershed (the lake plus the area of vegetation to the north), based on 9.27 million gal required to maintain the water level in the lake, is 4.34 m (14.25 ft) per year.

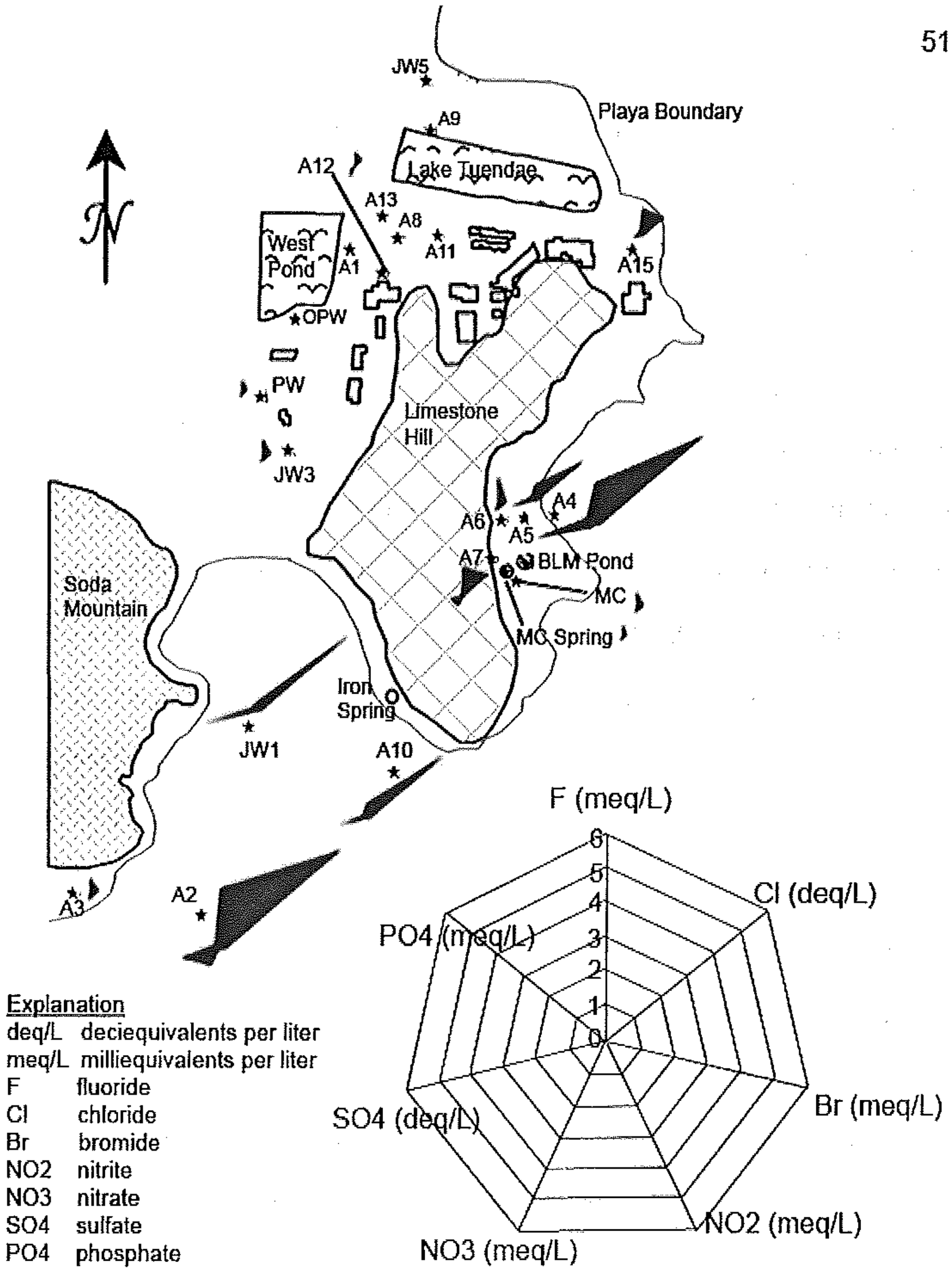


Figure 15. Anion Content of MC Spring and Groundwater. The wells on the playa have higher anion contents than the wells in the alluvial aquifer, and MC Spring is chemically similar to the alluvial aquifer groundwater. Note that the chloride and sulfate contents are presented in deciequivalents rather than milliequivalents per liter (100 times the concentrations).

Lake Tuendae

Lake Tuendae receives aquifer water to maintain its depth, temperature, and quality so the water remains habitable by the Mohave tui chub. More water was pumped into the Lake during the months in which elevated temperatures cause greater evaporation (September, May, June, July, and August); over a million gallons were added to Lake Tuendae during each of those months (Appendix C). In the same months, the amount of water added to the reservoir was also increased in response to variations in the domestic needs of the Desert Studies Center.

Source for MC Spring

As presented in Chapter 1, two distinct aquifer systems underlie the Zzyzx and Soda Lake area. Besides location, distinct groundwater elevations (Figures 9 and 10), groundwater quality (Figures 12 and 13), and anion chemistry (Figure 15) are most useful in illustrating the differences between the two aquifers. The groundwater elevation, quality, and anion chemistry of MC Spring are more similar to the alluvial aquifer wells than to the playa aquifer wells. These comparisons indicate that although MC Spring is located very close to the edge of the Soda Lake playa, the spring is fed by the alluvial aquifer, not by the playa aquifer.

Recharge Rate

Recharge would be best understood by monitoring water levels for tens of years in this area of highly variable annual precipitation. The recharge rate is determined by comparing rainfall events to groundwater surface increases (by monitoring water levels in wells). Again, it is important to note that 2006-2007 was an abnormally dry year, as presented in Chapter 1. Because of this unusual precipitation season, it is difficult to draw any conclusions about groundwater elevations with respect to precipitation.

<u>Resistivity South of Limestone Hill</u>

The extent of the playa aquifer can be interpreted from the resistivity survey. In general, lower resistivity occurs when the geology is of tighter formation, or in moist to wet conditions. The dark blue areas of the processed cross-section in Figure 16 are interpreted as moist to wet clay underlying the playa surface. The clay pinches out at the far western edge of the cross section and the resistivity is indicative of moist silt and sand. At the surface, this area is alluvium rather than playa so the courser-grained materials are expected. The highest resistivity values shown in orange and red in lower portion of the cross-section are interpreted as dry, slightly fractured rock. This may indicate the subsurface extension of Limestone Hill. Likewise, the higher resistivity (yellow) at a depth of approximately 20 to 30 m (65 to 100 ft) in the west may indicate the subsurface extension of the southern extent of Soda Mountain. Other than the high resistivity portions which may indicate dry, fractured rock, wet clay and silt appears to extend to the total surveyed depth of over 80 m (250 ft).

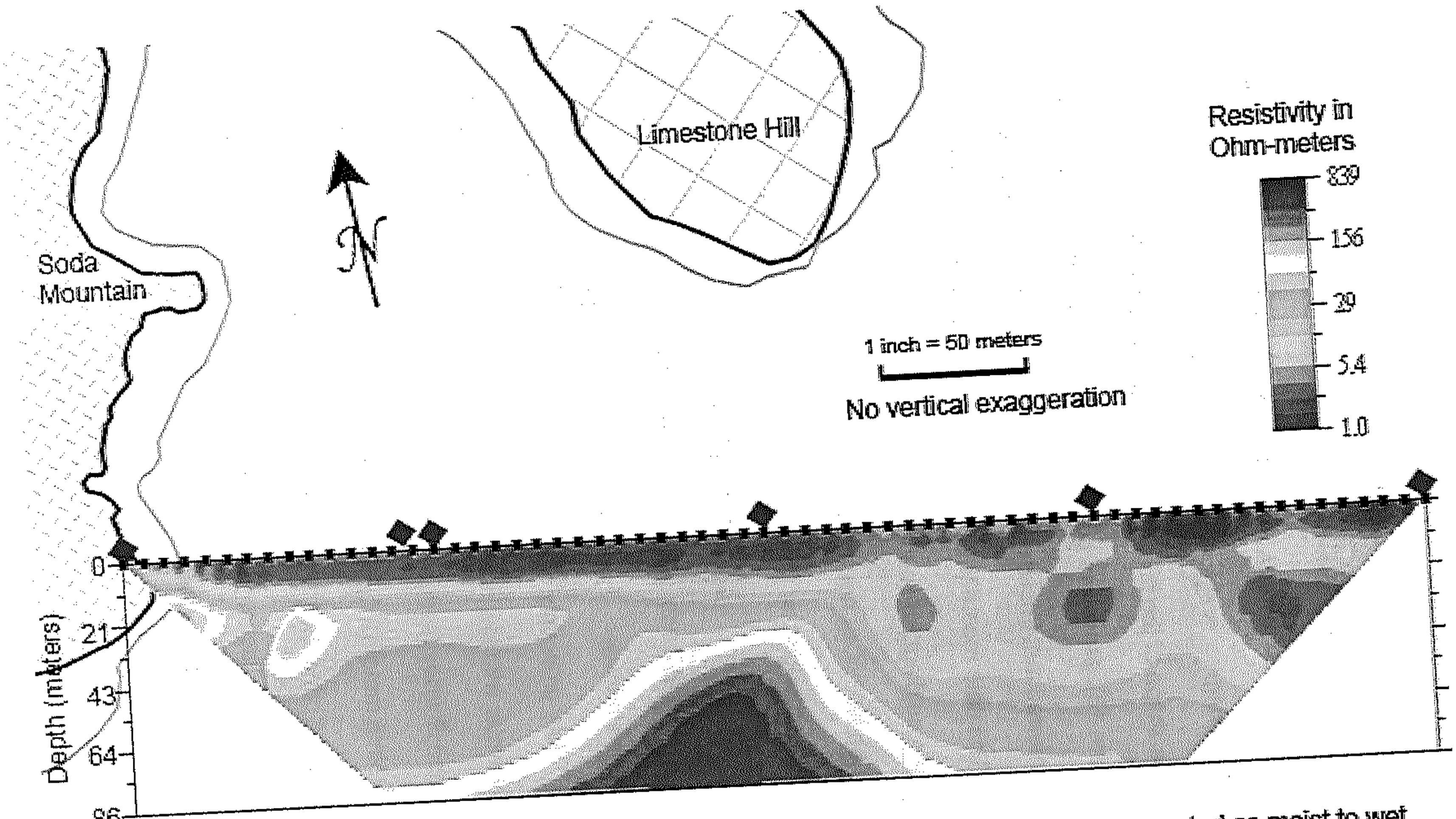


Figure 16. Resistivity South of Limestone Hill. Darker blue areas indicate low resistivity, interpreted as moist to wet sediments. Darker red areas indicate high resistivity, interpreted as dry, slightly fractured rock.

Fractures in Limestone Hill

The orientation of fractures in Limestone Hill (Figure 17) is consistent with the groundwater elevation, quality, and anion chemistry patterns recorded in the wells and in MC Spring.

Based on the shape of the hill and the saddle that shows in the aerial photograph (Figure 18), as well as the results of contouring the groundwater elevations, it is inferred that fractures are predominant in the southern half of Limestone Hill. The data recorded during the fracture survey are presented in Appendix F. The rose diagram shows the dominant fracture direction in Limestone Hill to be N83W, or nearly east-west. This fracture system provides a possible conduit for groundwater from the alluvial aquifer to feed MC Spring.

Zzyzx Vegetation

Vegetation patterns at Zzyzx (Figures 19 and 20) provide insight to the depth and quality of the groundwater. *Typha* (cattails), and *Phragmites* (reed grass) are hydrophytes. They grow only where water is exposed at the surface, and generally indicate water with low total dissolved solids and EC (Meinzer 1927). *Juncus* (rushes) and *Scirpus* (sedges) occur on the edges of the water bodies, where water is within a meter (3 ft) of the ground surface. These four species were observed at MC Spring, BLM Pond, Iron Spring, and Lake Tuendae; these wetlands indicate areas of discharge from the surface water into the surrounding sediments. *Anemopsis* (yerba mansa) also requires groundwater to be within approximately 1.5 m (5 ft) from the ground

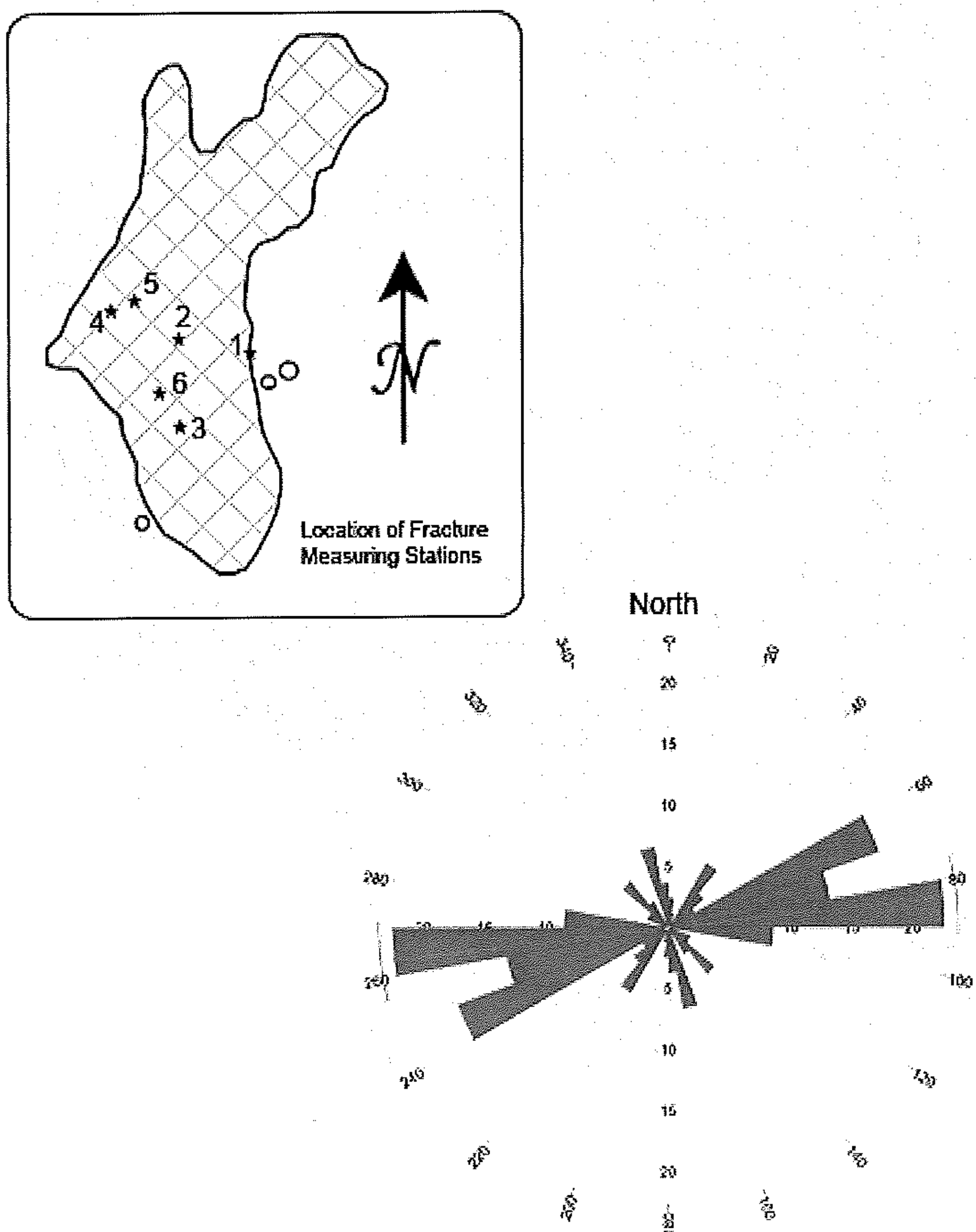


Figure 17. Fracture System in Limestone Hill. This rose diagram shows the dominant fracture direction in Limestone Hill.

Figure 18. Fracture Zone in Limestone Hill. Between the green lines Limestone Hill is more weathered, forming a saddle in the hill. Fractures may be more prominant in this area.

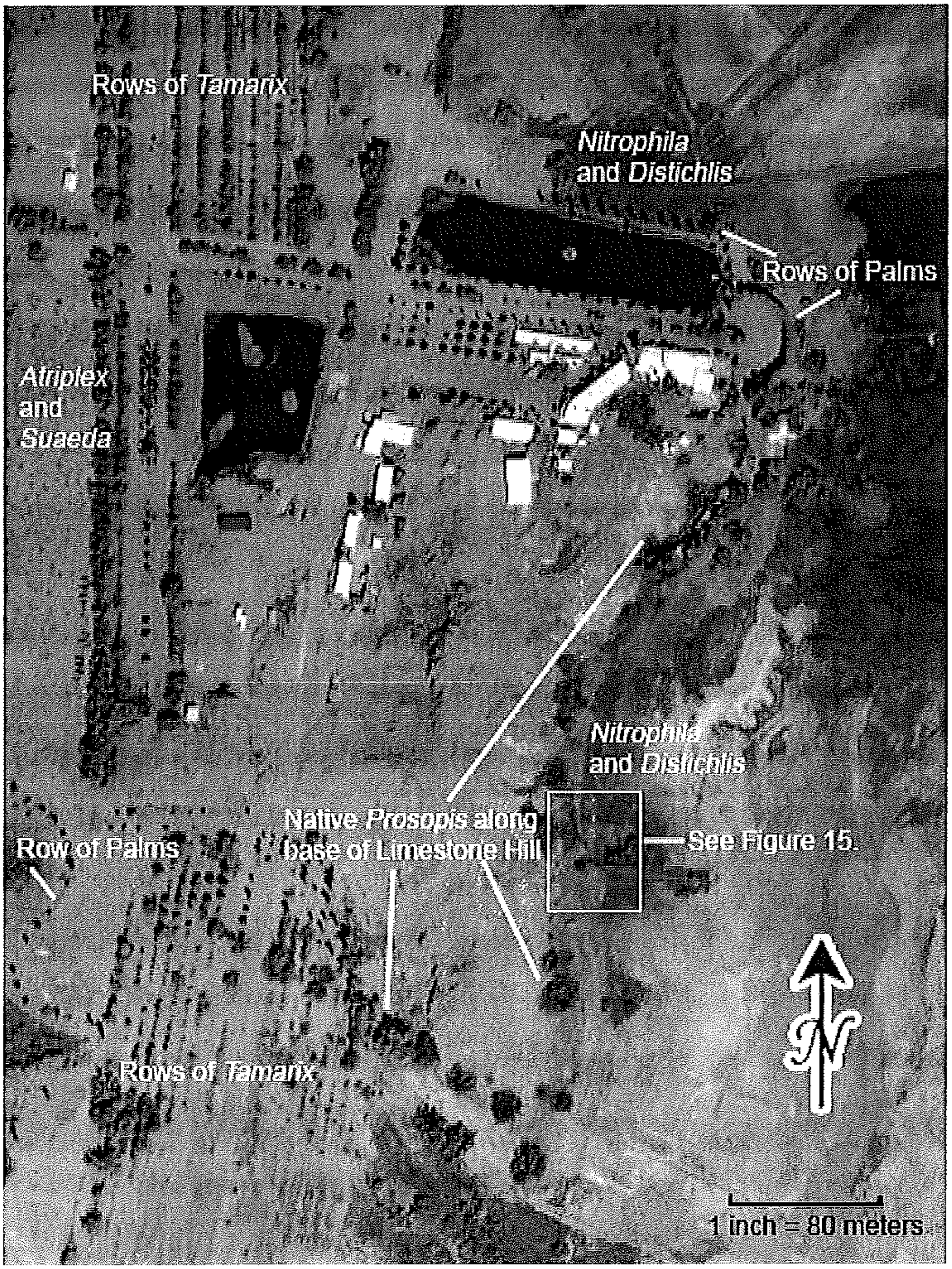


Figure 19. Vegetation at Zzyzx Desert Studies Center. Palm and *Tamarix* are introduced trees. *Nitrophila* and *Distichles* indicate water within 2.5 meters of the ground surface. *Proposis* do not tolerate water of poor quality.

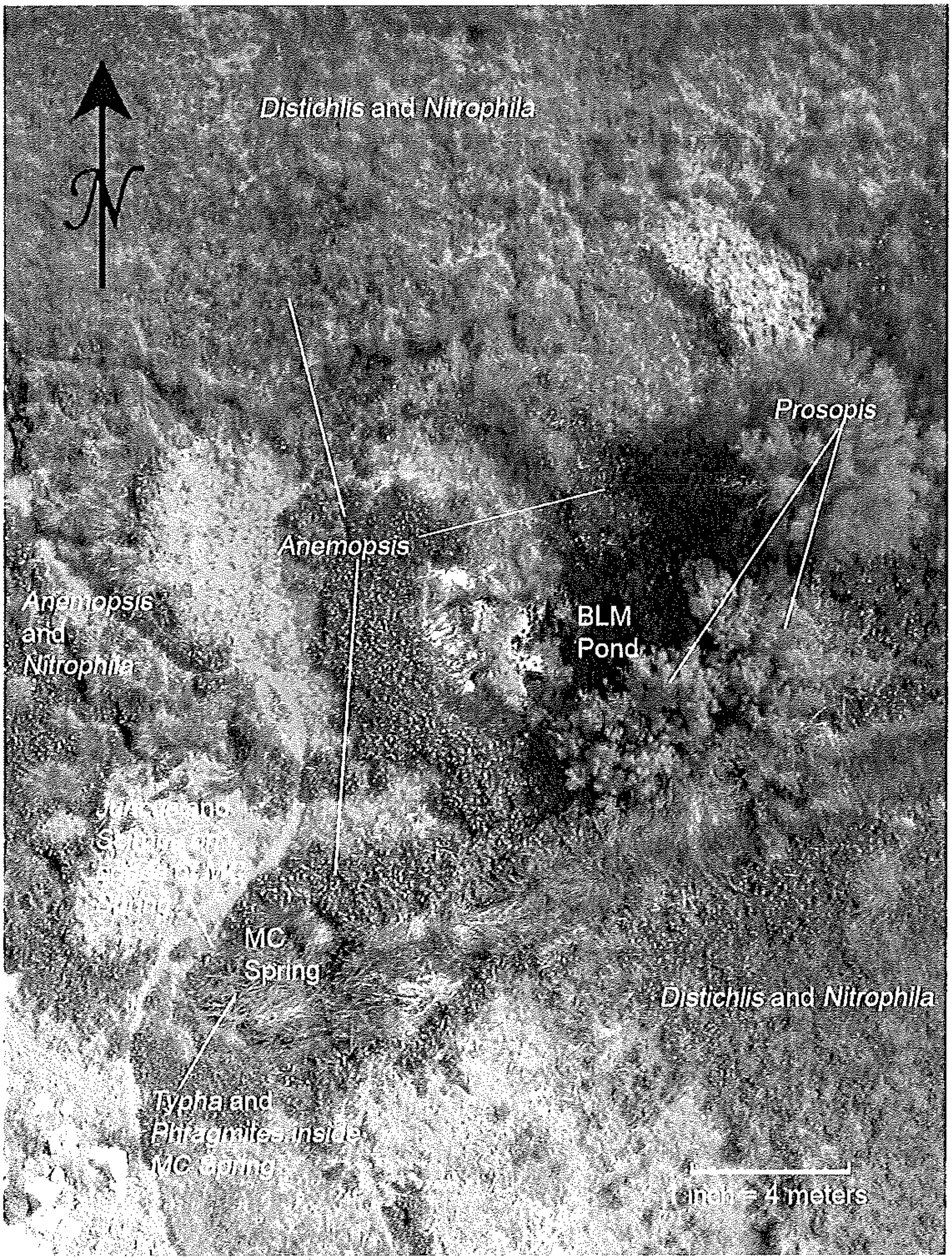


Figure 20. Vegetation in the Vicinity of MC Spring. Hydrophylic *Typha* and *Phragmites* grow within the spring; *Juncus* and *Scirpus* occur on the edges of the spring. *Anemposis*, *Nitrophila*, and *Distichlis* indicate shallow groundwater.

surface (Meinzer 1927). *Anemopsis* is prominent on the eastern side of Limestone Hill between the hill and Soda Lake playa. A few *Anemopsis* were also found at Iron Spring and along the north shore of Lake Tuendae. *Distichlis* (saltgrass) can tolerate fresh or alkaline conditions, and can reach groundwater as far as 2.5 m (8 ft) below the ground surface (Meinzer 1927). *Nitrophila* (Nitrophilia) is commonly associated with *Distichlis* (Meinzer 1927). These two halophytic species are wide-spread throughout Zzyzx, extending from near the surface water locations outward toward the playa. *Atriplex* (salt bush) and *Suaeda* (iodine bush) tolerate alkaline conditions, and generally depend on soil moisture at or near the surface rather than on groundwater (Meinzer 1927). *Suaeda* and two species of *Atriplex* (desert holly and cattle spinach) are common in the alluvial deposits east of the Soda Mountains and west of Limestone Hill, and on Limestone Hill. Two species of *Tamarix* (deciduous Salt Cedar and evergreen Tamarisk, an introduced tree commonly planted as a windbreak or ornamentally) and *Phoenix* and *Washingtonia* Palm trees (also introduced at Zzyzx) are also halophytic and have widespread, shallow root systems that reach downward to the capillary zone above the water table (Meinzer 1927). Rows of *Tamarix* and Palms were planted by Curtis Springer throughout Zzyzx as nursery stock. Most of these trees thrive at Zzyzx. Native *Prosopis* (Mesquite) trees, as well as the introduced *Tamarix*, are also known to send a taproot as deep as 15 m (50 ft) below the ground surface in search of groundwater. *Prosopis* is not tolerant of poor water quality (Meinzer 1927).

Aquifer Test Data

Average results of previous studies on groundwater conditions performed by undergraduate and graduate students are summarized in Table 3. Hydraulic conductivity (K) was reported from 4,580 gallons per day per square foot (gpd/ft^2) to 9,160 gpd/ ft^2. Transmissivity (T) was reported from 27,000 gpd/ft to 792,000 gpd/ft. The coefficient of storage (S), or specific yield, was reported between 0.000075 and 19.1. Based on these values, the estimated radius of influence (r_0) was calculated based upon the time of pumping, T, and S values. Although r_0 varied in response to the other values, the greatest r_0 was calculated to be 101 m (330 ft) (Table 3). The only observation wells within this radius are Wells OPW and JW3. The distance to MC Spring is approximately 215 m (705 ft) when measured directly through Limestone Hill. Because the distance to MC Spring is more than twice r_0, pumping of groundwater for use at the Studies Center and to maintain the depth of Lake Tuendae has no effect on MC Spring. Refer to Figure 3 for the locations of the wells and MC Spring.

Water Budget

A water budget is calculated with the equation (Fetter 1994):

Inflow = Outflow +/- Change in Storage

Water budgets for Lake Tuendae and MC Spring are presented in Table 4. Inflow factors in the 2-acre Lake Tuendae hydrogeology system include precipitation, rare overland flow, and recirculation of water used at the facility. Outflow factors include evapotranspiration, consumption, and groundwater

Table 3. Summary of Average Hydraulic Conditions at Zzyzx

Aquifer Test Date	pump rate (gpm)	t (minutes)	K (gpd/ft^2)	T (gpd/ft)	S (no units)	Q (gpd)	r_0 (meters)
January 1985[a]	218	1,000	-	1.00E+05	1.30E-01	-	10
November 1993[b]	148	1,000	6.87E+03	3.94E+05	5.50E-03	-	101
April 1995[c]	142	245	-	4.01E+05	3.74E-03	-	61
April 1995[d]	142	240	-	4.74E+05	4.10E-03	3.08E+06	63
November 1996[e]	150	1,200	-	4.98E+05	3.06E+00	5.07E+05	5

Notes:

Values for t, K, T, S, and Q reported by cited authors; r_0 calculated

[a] Bilhorn and Feldmeth 1985; test was performed on OPW. Time of pumping was assumed, not reported.

[b] Archbold 1994

[c] Brown 1995

[d] Dirling 1995

[e] Gardiner 1996

ft foot
ft^2 square foot
gpd gallons per day
gpm gallons per minute
K hydraulic conductivity

Q discharge
r_0 estimated radius of influence
S Storativity
t time
T Transmissivity

Table 4. Water Budget for Lake Tuendae and MC Spring

Factors	Descriptions	Values (acre-feet per year)
Lake Tuendae		
Inflow		
Precipitation	Average rainfall 3.4 inches per year*	0.6
Pumping	28.5 acre-feet/year	28.5
Overland Flow	Rare; during years of extreme flooding	0.0
Replacement	90% return of consumed/used water	3.6
Outflow		
Lake Tuende Evapotranspiration	28.5 acre-feet pumped into lake in the year	-28.5
Ground Water Seepage	Included in evapotranspiration	0.0
Usage at Studies Center	Pumped into pool and reservoir	-4.0
Changes in Storage		
Surface Water	No overall change	0.0
Balance		0.2
MC Spring		
Inflow		
Precipitation	Average rainfall 3.4 inches per year*	0.1
Calculated Inflow	Minimum 5.7 acre-feet/year**	5.7
Outflow		
MC Spring Evapotranspiration	Based on 14.25 ft/yr at Lake Tuendae	-5.7
Ground Water Seepage	Included in evapotranspiration	0.0
Changes in Storage		
	No overall change	0.0
Balance		0.1

Notes: Lake Tuendae watershed is 2 acres; MC Spring watershed is 0.4 acres.
* Source: National Park Service 1999
** Calculated inflow at MC Spring equals evapotranspiration, as evidenced by zero change in storage.

Pump Data: 32.4 acre-feet pumped in one year: 28.5 to Lake Tuendae; 0.39 to pool; 3.6 to reservoir.

seepage. The calculated evapotranspiration of the 2-acre Lake Tuendae watershed is 4.34 m (14.25 ft) per year as described above. Consumption was determined by the amount of water that was pumped into the reservoir for drinking, washing, and other uses at the Studies Center, and into the pool during the hot seasons (Appendix C). Groundwater elevations recorded between 1985 and 2007 show that the water table elevation in Zzyzx monitoring wells has not changed measurably; therefore, the long-term change in storage is negligible.

The steady water surface in the MC Spring indicates there is no overall change in storage in the spring. Therefore, the evapotranspiration (outflow) from the 0.4-acre MC Spring watershed is balanced by the inflow from precipitation and recharge through Limestone Hill.

Hydrogeologic Model

The hydrogeologic model (Figure 21) was prepared with information from synthesis of reference materials along with field observations, including water table elevations and water quality, of monitoring wells at Zzyzx and at MC Spring and Lake Tuendae. The model shows fractures in Limestone Hill consistent with a through-going providing a reasonable pathway for groundwater to recharge MC Spring from the alluvial aquifer west of Limestone Hill.

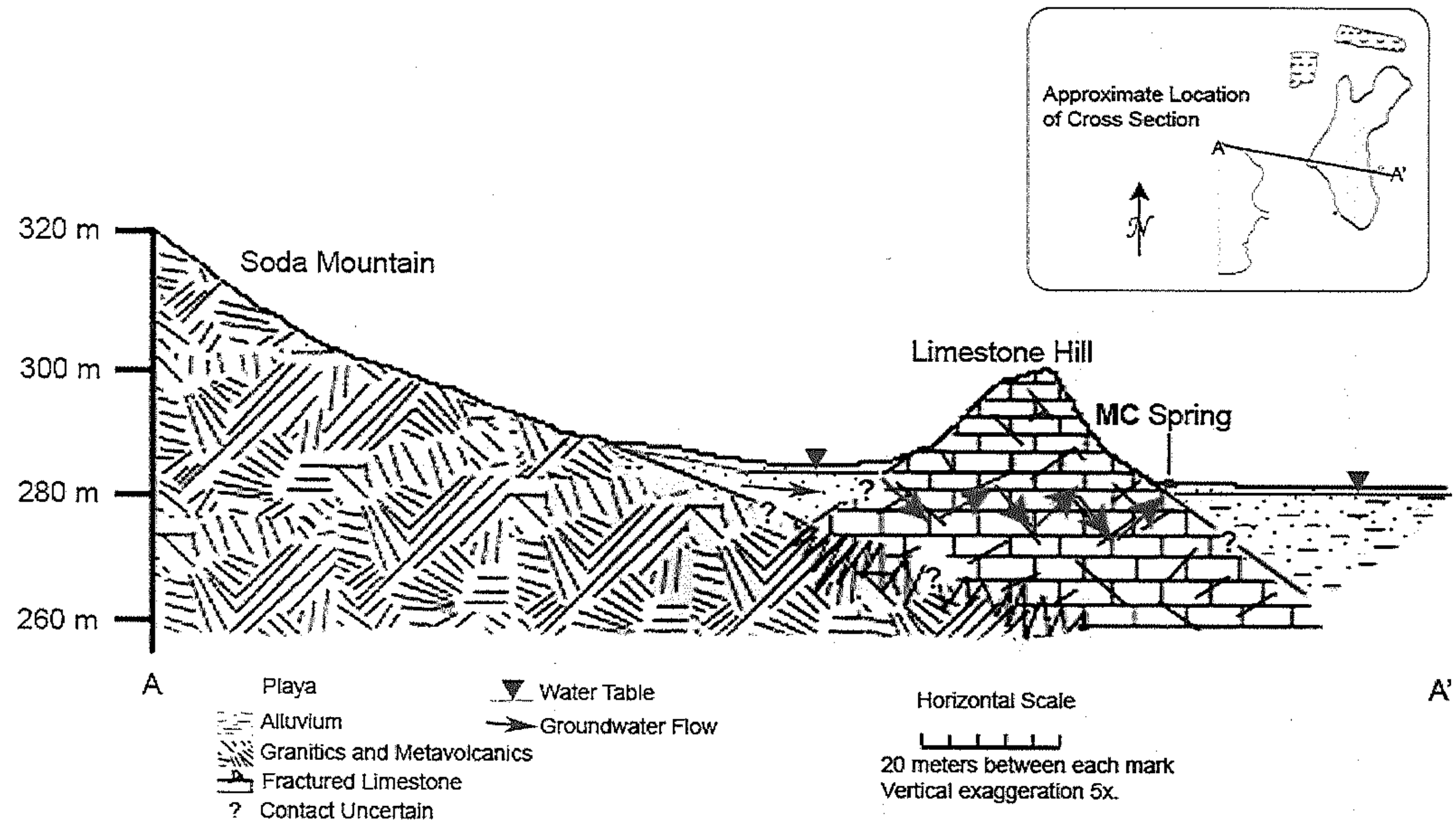


Figure 21. Hydrogeologic Model of Zzyzx Desert Studies Center. Conceptual cross section shows relationships between Soda Mountain, Limestone Hill, alluvial deposits, playa deposits, and groundwater. Subsurface contacts are uncertain. Fractures in Limestone Hill provide a reasonable pathway for groundwater to travel from the alluvial aquifer through Limestone Hill to MC Spring.

CHAPTER 5

CONCLUSIONS AND LONG-TERM STUDIES

Conclusions

MC Spring is recharged from the alluvial aquifer west of Limestone Hill, rather than from the playa aquifer. Fractures in Limestone Hill provide a possible mechanism for groundwater in the alluvial aquifer to recharge MC Spring.

The elevation of the water table, determined by field monitoring and the GPS survey, is 1 to 2 m (3 to 6 ft) higher in the alluvial aquifer and in MC Spring than the water table elevation in the playa aquifer.

Lake Tuendae is cut into the playa aquifer and the elevation of water in is maintained by pumping groundwater from the alluvial aquifer (using Well PW) into the lake. West Pond, which is cut into alluvial deposits, is located close to Well PW, yet is not affected (lowered) by pumping from the alluvial aquifer.

Chemical laboratory results and EC measurements imply that the water in MC Spring is very similar chemically to the alluvial aquifer, not to the playa aquifer. The playa aquifer groundwater contains very high concentrations of Cl, SO_4, and other anions. By contrast groundwater in the alluvial aquifer has lower overall concentrations and has a relatively greater concentration of F than the playa aquifer. Concentrations of EC are likewise more elevated in the playa aquifer when compared to the groundwater in the alluvial aquifer and MC Spring.

Vegetation patterns at Zzyzx reveal information about groundwater depth and quality in areas where no wells are available to monitor groundwater. Heavy growth of *Nitrophila* and *Distichlis* shows areas where water discharges north of Lake Tuendae and surrounding MC Spring and Iron Spring. In the vicinity of Iron Spring and MC Spring, *Typha*, *Phragmites*, *Juncus*, and *Scirpus* indicate water of relatively good quality at or very near the ground surface.

A fracture system through Limestone Hill is most prevalent in the southern portion of the hill. The fractures are predominantly in an east-west direction, in line with MC Spring.

Because Zzyzx Desert Studies Center is a closed system, all of the water that enters the system stays within the system. Therefore, pumping volumes that were monitored in 2006 and 2007 provided a basis to calculate an evapotranspiration rate, which was used to calculate a water budget for Lake Tuendae. Those values, in turn, were used to calculate a balanced water budget for MC Spring that coincides with the observation that the water level in the spring was constant throughout the study period. All outflow from the system (through evapotranspiration) was compensated by inflow from precipitation and from recharge from the alluvial aquifer through fractures in Limestone Hill.

Recommended Future Studies

A resistivity survey between the southern extent of Soda Mountain and Limestone Hill is recommended to further characterize the relationships between the alluvial aquifer, Soda Mountain, and Limestone Hill. Surveys are also recommended across Limestone Hill in both directions to further study the fractures in Limestone Hill and its subsurface extent.

This study was performed in an extremely dry year at Zzyzx. In order for a valuable study to be carried out, long-term monitoring is necessary, to compare rainfall and water levels on a scale of decades rather than months. The analysis included in this report can be used as a baseline for long-term monitoring of the groundwater and surface water conditions at Zzyzx.

A limited understanding of subsurface geology was gained by the logs of the hand-augered boreholes. Piezometers should be installed in areas where there are gaps in the groundwater and geology data. These should be advanced with drill rigs, rather than by hand-auger, to prevent shallow refusal. Accurate geological logging during drilling of the boreholes would provide a better knowledge of the subsurface geology, and may help determine the subsurface extent of Limestone Hill.

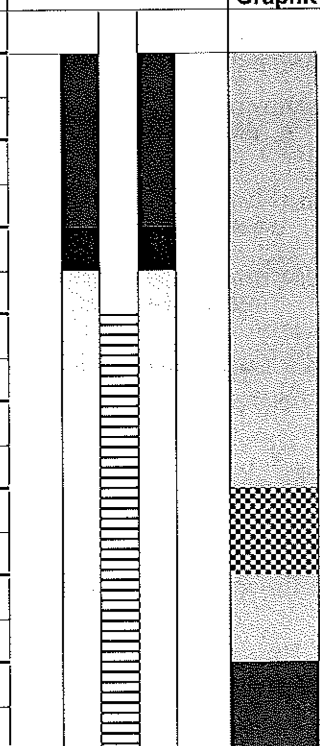
The surface water analysis provides baseline data that can be useful for the preservation and management, and possible expansion, of the habitat of the Mohave tui chub.

APPENDIX A

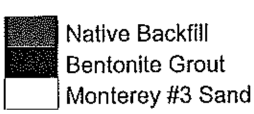
BOREHOLE LOGS

BOREHOLE/WELL CONSTRUCTION LOG

Project Name:	Soda Springs Desert Studies Center			**Borehole Number:**	A1
Borehole Location:	Wellfield between Lake Tuende and LS Hill			**Total Depth (bgs):**	8.0 feet
Drilling Agency:	CSUF	**Driller:**		**Depth to Bedrock:**	8.0 feet
Drilling Equipment	Hand Auger	**Date Started:**	10/16/96	**Depth to Water**	
Drilling Method:	Hand Auger	**Date Finished:**	10/16/96	**(Drilling):**	3.92 feet
Drilling Fluid:	None	**Number of Samples:**		**(Static):**	feet
Completion Information:		**Borehole Diameter:**	3.5 inches	**Elevation TOC:**	936.13 feet
Completed as a 2" monitoring well		**Logged By:**		**Datum:**	msl
Northing:	2242653	**Easting:**	7128321.36	**Stickup (feet):**	



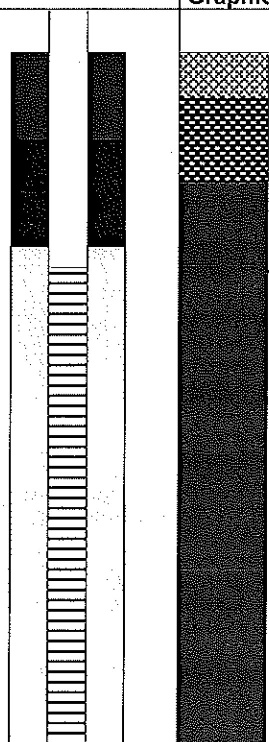
Depth (feet)	Log Graphic USCS	Lithologic Description
0.0		**Round concrete pad installed at surface**
0.5	GW	SANDY GRAVEL; gray brown; subangular to subroun gravel in carbonate-rich matrix; poorly sorted
1.0		larger subrounded gravel clsts in limestone-rich matrix
1.5		
2.0		
2.5		
3.0		
3.5		
4.0		
4.5		
5.0		
5.5	SW	PEBBLY SAND; gray brown; poorly-sorted subangular limestone-rich clasts
6.0		
6.5	GW	SANDY GRAVEL; gray brown; subangular to subroun limestone rich gravel; poorly-sorted
7.0		
7.5	SW	SAND; limestone-rich; coarse; subrounded; moderate sorted
8.0		
8.5		Total Depth 8.0 feet
9.0		
9.5		
10.0		



BOREHOLE/WELL CONSTRUCTION LOG

Project Name: Soda Springs Desert Studies Center		**Borehole Number:** A4
Borehole Location: beyond playa boundary east of Limestone Hill		**Total Depth (bgs):** 14.0 feet
Drilling Agency: CSUF	**Driller:**	**Depth to Bedrock:** feet
Drilling Equipment Hand Auger	**Date Started:** 10/16/96	**Depth to Water**
Drilling Method: Hand Auger	**Date Finished:** 10/16/96	**(Drilling):** feet
Drilling Fluid: None	**Number of Sample:** 14	**(Static):** feet
Completion Information:	**Borehole Diameter:** 3.5 inches	**Elevation TOC:** 931.03 feet
Completed as a 2" monitoring well	**Logged By:** Jan and Angie	**Datum:** msl
Northing: 2243072	**Easting:** 7128620.32	**Stickup (feet):**

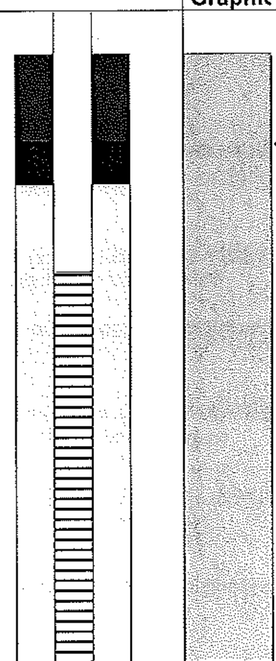
Depth (feet)	**Well Design**	**Log Graphic USCS**	**Lithologic Description**
0.0			**Round concrete pad installed at surface**
1.0			SALT EVAPORITE; gray; brittle; subhedral crystals
2.0		CL	SANDY SILTY CLAY; cinnamon-brown; poorly sorted (silt, very fine sand); quartz, biotite; moist (cohe[sive but] clumpy); immature texture; plant roots
3.0			
4.0		ML	CLAYEY SILT; cinnamon-brown; poorly sorted; quartz, biotite; moist (cohesive but clumpy) interbedded with SILT; cinnamon-brown; very fine to medium pebble cla[sts]; poorly sorted; quartz, biotite; immature texture
5.0			
6.0			
7.0			at 5' color change to olive brown; pyrite, muscovite
8.0			
9.0			
10.0			plant fragments
11.0			
12.0			salt crustation on drying samples
13.0			
14.0			
15.0			Total Depth 14.0 feet
16.0			
17.0			
18.0	well design not logged		
19.0			
20.0			



Native Backfill
Bentonite Grout
Monterey #3 Sand

BOREHOLE/WELL CONSTRUCTION LOG

Project Name: Soda Springs Desert Studies Center		**Borehole Number:**	A8
Borehole Location: wellfield between Lake Tuende and LS Hill		**Total Depth (bgs):**	7.0 feet
Drilling Agency: CSUF	**Driller:**	**Depth to Bedrock:**	feet
Drilling Equipment Hand Auger	**Date Started:** 10/16/96	**Depth to Water**	
Drilling Method: Hand Auger	**Date Finished:** 10/16/96	**(Drilling):**	4.78 feet
Drilling Fluid: None	**Number of Sample** 5	**(Static):**	feet
Completion Information:	**Borehole Diameter:** 3.5 inches	**Elevation TOC:**	936.99 feet
Completed as a 2" monitoring well	**Logged By:** Jan and Angie	**Datum:** msl	
Northing: 2242651.14	**Easting:** 7128205.54	**Stickup (feet):**	

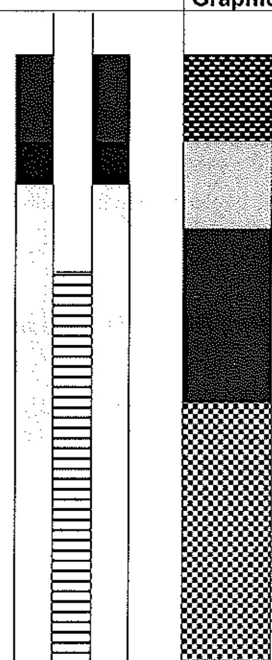


Depth (feet)	Log Graphic USCS	Lithologic Description
0.0		**Round concrete pad installed at surface**
0.5	SW	GRAVELLY SILTY SAND; tan; poorly sorted; subangu subrounded, silt to coarse pebble, limestone an fragment clasts; dry; immature texture; pl salty taste; some caliche
1.0		
1.5		at 1' color change to greenish gray
2.0		
2.5		
3.0		
3.5		very fine to coarse pebble size mafic, igneous, sedime fragments
4.0		
4.5	SW	GRAVELLY SAND; tan gray; subangular to subrounde fine sand to coarse pebble; quartz, biotite, lithic dry
5.0		
5.5		
6.0		
6.5		
7.0		
7.5		Total Depth 7.0 feet
8.0		
8.5		
9.0		
9.5		
10.0		

Native Backfill
Bentonite Grout
Monterey #3 Sand

BOREHOLE/WELL CONSTRUCTION LOG

Project Name:	Soda Springs Desert Studies Center			**Borehole Number:**	A10
Borehole Location:	near playa boundary south of Limestone Hill			**Total Depth (bgs):**	7.0 feet
Drilling Agency:	CSUF	**Driller:**		**Depth to Bedrock:**	feet
Drilling Equipment	Hand Auger	**Date Started:**	10/28/96	**Depth to Water**	
Drilling Method:	Hand Auger	**Date Finished:**	10/28/96	**(Drilling):**	feet
Drilling Fluid:	None	**Number of Samples**	5	**(Static):**	feet
Completion Information:		**Borehole Diameter:**	3.5 inches	**Elevation TOC:**	931.75 feet
Completed as a 2" monitoring well		**Logged By:**		**Datum:**	msl
Northing:	35.13944	**Easting:**	-116.10487	**Stickup (feet):**	1.02



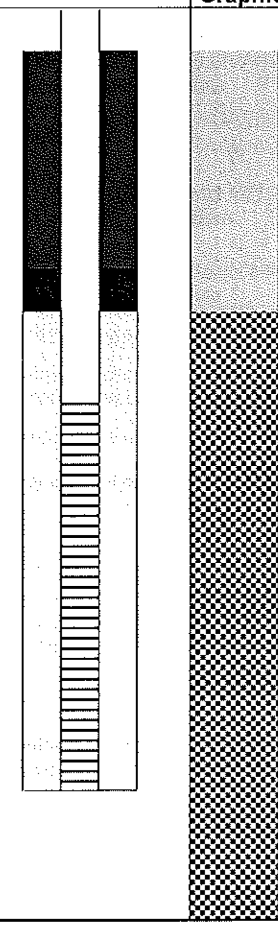
Depth (feet)	Log Graphic USCS	Lithologic Description
0.0		**Round concrete pad installed at surface**
0.5	CL	SILTY CLAY; chocolate brown; immature texture; salty plant fragments
1.0		
1.5	SM	SILTY SAND; olive brown; slightly moist
2.0		
2.5	ML	SANDY SILT; dark tan; very fine quartz and black lithic sand; poorly sorted; dry; immature texture
3.0		
3.5		grading to olive brown; fine to coarse sand
4.0		
4.5	SW	GRAVELY SAND; olive brown; moderately sorted; rou coarse sand to small pebbles of limestone and clasts
5.0		
5.5	SP	SAND; gray brown; well-sorted; well-rounded; quartz, biotite sand; wet; mature texture
6.0		
6.5		grading to olive brown; moist
7.0		
7.5		Total Depth 7.0 feet
8.0		
8.5		
9.0		
9.5		
10.0		

well design not logged

Native Backfill
Bentonite Grout
Monterey #3 Sand

BOREHOLE/WELL CONSTRUCTION LOG

Project Name:	Soda Springs Desert Studies Center			**Borehole Number:**	A12
Borehole Location:	in caretakers yard			**Total Depth (bgs):**	10.0 feet
Drilling Agency:	CSUF	**Driller:**		**Depth to Bedrock:**	feet
Drilling Equipment	Hand Auger	**Date Started:**	10/16/96	**Depth to Water**	
Drilling Method:	Hand Auger	**Date Finished:**	10/16/96	**(Drilling):**	~7 feet
Drilling Fluid:	None	**Number of Samples:**		**(Static):**	feet
Completion Information:		**Borehole Diameter**	3.5 inches	**Elevation TOC:**	938.03 feet
Completed as a 2" monitoring well		**Logged By:**		**Datum:**	msl
Northing:	2242720.48	**Easting:**	7128258.04	**Stickup (feet):**	



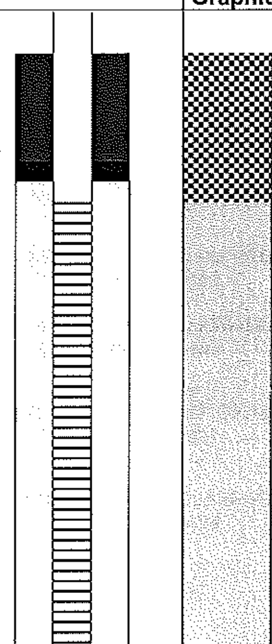
Depth (feet)	Log USCS	Lithologic Description
0.0		**Round concrete pad installed at surface**
0.5	SM	Dry top soil
1.0		
1.5		SILTY SAND; dark tan; very fine sand to fine pebbles; quartz and dark granite, 5% unconsolidated part sorted; angular
2.0		
2.5		color change to tan; grading to very fine sand to mediu pebbles; chert, quartz, epidote; grading to subrc
3.0		
3.5	SW	GRAVELLY SAND; coarse sand to coarse gravel; chlo inclusions in epidote, quartz; poorly sorted; very rounded
4.0		
4.5	SP	SAND; tan; quartz, plagioclase; well sorted; very well rounded
5.0		
5.5	SW	GRAVELLY SAND; coarse sand to fine cobble; chlorit inclusions in epidote, quartz; poorly sorted; angu rounded
6.0		
6.5		
7.0		
7.5		grading to slightly moist
8.0		
8.5		grading to medium sand to medium pebbles; rading to slightly moist
9.0		
9.5		
10.0		Total Depth 10.0 feet

Native Backfill
Bentonite Grout
Monterey #3 Sand

BOREHOLE/WELL CONSTRUCTION LOG

Project Name: Soda Springs Desert Studies Center		**Borehole Number:**	A15
Borehole Location: east end of Blvd of Dreams		**Total Depth (bgs):**	14.2 feet
Drilling Agency: CSUF	**Driller:**	**Depth to Bedrock:**	feet
Drilling Equipment Hand Auger	**Date Started:** 10/25/96	**Depth to Water**	
Drilling Method: Hand Auger	**Date Finished:** 10/26/96	**(Drilling):**	feet
Drilling Fluid: None	**Number of Samples:**	**(Static):**	feet
Completion Information:	**Borehole Diameter:** 3.5 inches	**Elevation TOC:**	935.13 feet
Completed as a 2" monitoring well	**Logged By:**	**Datum:** msl	
Northing: 35.14276	**Easting:** -116.10298	**Stickup (feet):**	

Depth (feet)	Well Design	Log Graphic USCS	Lithologic Description
0.0			**Round concrete pad installed at surface**
1.0		SW	GRAVELLY SAND; brown; subrounded, fine, quartz/bi sand; large angular fragments of limstone/lithics pebble size increases with depth; root fra
2.0			
3.0			
4.0		SM	SILTY SAND; brown; silty to very fine, subrounded, moderately sorted sand; angular coarse grained and lithic fragments; root fragments
5.0			at 4' color golden brown; quartz/biotite/muscovite/felds sand; grading with rounded granitoid clasts
6.0			at 5' color change to greenish-brown; grading to slightly moist
7.0			at 6' color change to brownish-green; grading to well s grading to well rounded
8.0			at 7' color change to grey-brown
9.0			at 8' color change to greenish-gray; few pieces of calic present
10.0			
11.0			
12.0			
13.0			
14.0			
15.0			Total Depth 14.18 feet
16.0			
17.0			*color becomes gradually lighter with depth; omposition stays the same.
18.0			
19.0			
20.0			

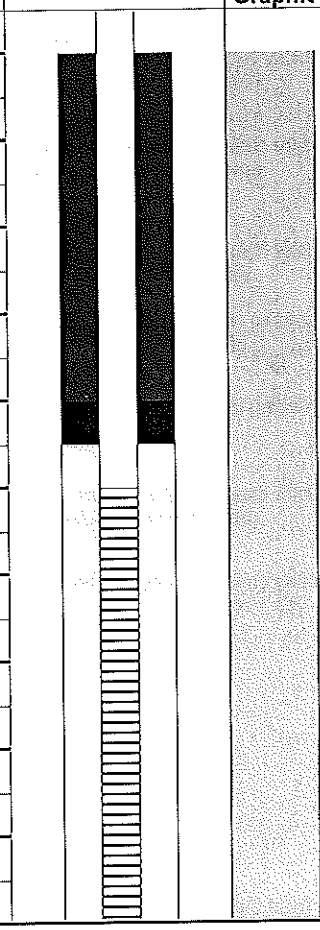


Native Backfill
Bentonite Grout
Monterey #3 Sand

BOREHOLE/WELL CONSTRUCTION LOG

Project Name: Soda Springs Desert Studies Center		**Borehole Number:**	JW3
Borehole Location: near diesel storage tank		**Total Depth (bgs):**	10.0 feet
Drilling Agency: CSUF	**Driller:**	**Depth to Bedrock:**	feet
Drilling Equipment Hand Auger	**Date Started:** 10/21/96	**Depth to Water**	
Drilling Method: Hand Auger	**Date Finished:** 10/21/96	**(Drilling):**	8.2 feet
Drilling Fluid: None	**Number of Samples:**	**(Static):**	feet
Completion Information:	**Borehole Diameter:** 3.5 inches	**Elevation TOC:**	941.15 feet
Completed as a 2" monitoring well	**Logged By:**	**Datum:** msl	
Northing: 2243075.04	**Easting:** 7128562.2	**Stickup (feet):**	

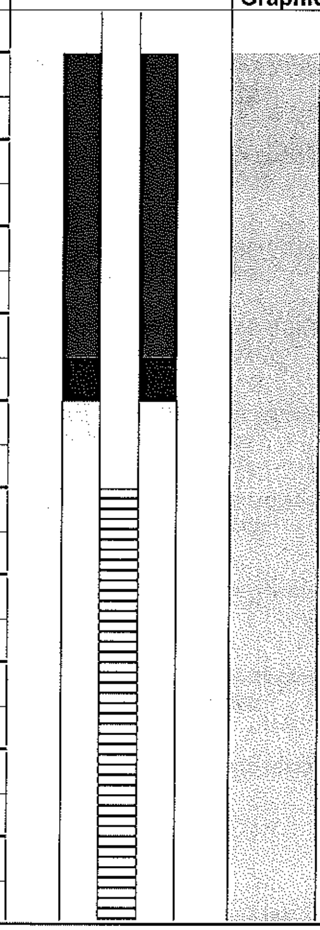
Depth (feet)	Well Design	Log Graphic	USCS	Lithologic Description
0.0				**Round concrete pad installed at surface**
0.5			SM	SILTY SAND; tan; grey quartz, limestone, basalt, cher pebbles; moderalely sorted; angular
1.0				
1.5				grading to poorly sorted; 90% sand; 10% fine to mediu pebbles
2.0				
2.5			GW	SILTY GRAVEL; tan; siltstone, limestone, epidote, qua anbular siltstone pebbles; rounded epidote pebl sorted
3.0				
3.5			SM	SILTY SAND; dark tan; quartz; well sorted; well round moist
4.0				
4.5				grading to poorly sorted; grading to angular; grading w volcanics; 15% pebbles
5.0				
5.5			GW	SANDY GRAVEL; grey-tan; limestone and quartz pebl and cobbles; poorly sorted; angular; dry
6.0				
6.5				grading without cobbles
7.0				
7.5				color change to greenish grey; caliche siltstone cobble pebbles; angular quartz sand; silt
8.0				
8.5				color change to grey
9.0				
9.5				
10.0				Total Depth 10.0 feet



Native Backfill
Bentonite Grout
Monterey #3 Sand

BOREHOLE/WELL CONSTRUCTION LOG

Project Name:	Soda Springs Desert Studies Center			**Borehole Number:**	JW4
Borehole Location:	northwest of Blvd. of Dreams			**Total Depth (bgs):**	10.0 feet
Drilling Agency:	CSUF	**Driller:**		**Depth to Bedrock:**	feet
Drilling Equipment	Hand Auger	**Date Started:**	10/14/96	**Depth to Water**	
Drilling Method:	Hand Auger	**Date Finished:**	10/14/96	**(Drilling):**	feet
Drilling Fluid:	None	**Number of Samples:**		**(Static):**	feet
Completion Information:		**Borehole Diameter:**	3.5 inches	**Elevation TOC:**	940.71 feet
Completed as a 2" monitoring well		**Logged By:**		**Datum:**	msl
Northing:		**Easting:**		**Stickup (feet):**	

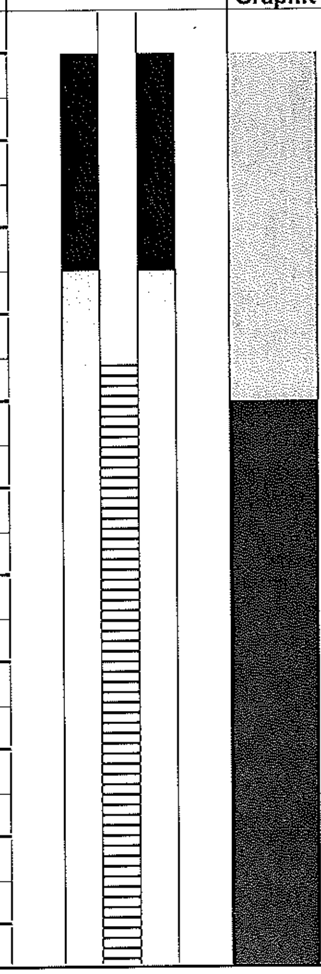


Depth (feet)	Well Design	Log Graphic	USCS	Lithologic Description
0.0				**Round concrete pad installed at surface**
0.5			SM	SILTY SAND; tan; fine quartz, biotite, feldspar, carbon (limestone) sand; poorly sorted; angular
1.0				
1.5				color change to beige-tan; grading to fine to coase sar grading to moderately sorted; grading to subang
2.0				
2.5				color change to beige; grading to very fine, well round matrix with angular, medium sand
3.0				
3.5				grading with angular limestone, other lithic pebble frag grading to moist
4.0				
4.5				grading to damp
5.0				
5.5				color change to grey-brown; grading to moderately so grading to subangular
6.0				
6.5				color change to beige; grading to well sorted; grading rounded
7.0				
7.5				
8.0				
8.5				
9.0				
9.5				
10.0				Total Depth 10.0 feet

Native Backfill
Bentonite Grout
Monterey #3 Sand

BOREHOLE/WELL CONSTRUCTION LOG

Project Name:	Soda Springs Desert Studies Center			**Borehole Number:**	MC
Borehole Location:	adjacent to MC Spring			**Total Depth (bgs):**	10.5 feet
Drilling Agency:	CSUF	**Driller:**		**Depth to Bedrock:**	feet
Drilling Equipment	Hand Auger	**Date Started:**	11/9/96	**Depth to Water**	
Drilling Method:	Hand Auger	**Date Finished:**	11/9/96	**(Drilling):**	feet
Drilling Fluid:	None	**Number of Samples:**		**(Static):**	feet
Completion Information:		**Borehole Diameter.**	3.5 inches	**Elevation TOC:**	933.01 feet
Completed as a 2" monitoring well		**Logged By:**		**Datum:**	msl
Northing:	2242902.56	**Easting:**	7128564.04	**Stickup (feet):**	

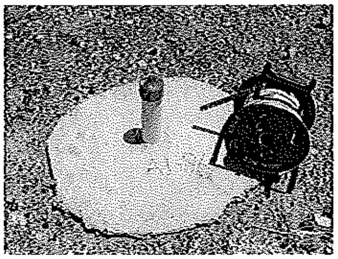


Depth (feet)	Log USCS	Lithologic Description
0.0		**Round concrete pad installed at surface** SILTY SAND; dark brown (10YR 3.3); well sorted; dry
0.5	SM	
1.0		
1.5		
2.0		
2.5		
3.0		color change to dark brown (10YR 3/2); very fine sand moist; plant fragments
3.5		
4.0		SANDY SILT; very dark brown (7.5YR 2.5/3), mottled (4/4); quartz sand; wet; plant roots
4.5	ML	
5.0		color change to brown (10YR 4/3)
5.5		
6.0		
6.5		
7.0		
7.5		
8.0		Noted as rock deposit from 8.5' to total depth. Limest noted at 10.5'
8.5		
9.0		
9.5		at 9.5' color change to mottled green; sulfur smell
10.0		
10.5		Total Depth 10.5 feet

Native Backfill
Bentonite Grout
Monterey #3 Sand

APPENDIX B

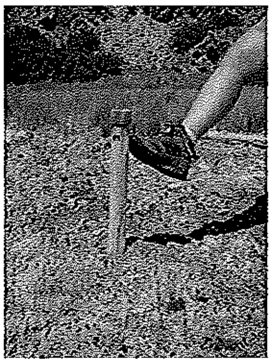
PHOTOGRAPHS OF GROUNDWATER MONITORING WELLS



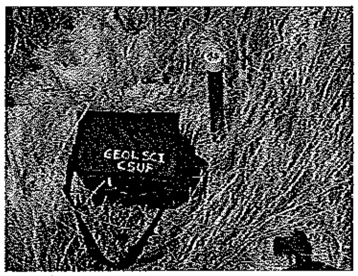
Well A1

Well A2

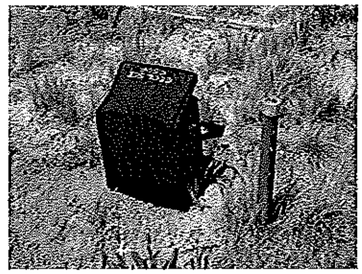
Well A3



Well A4

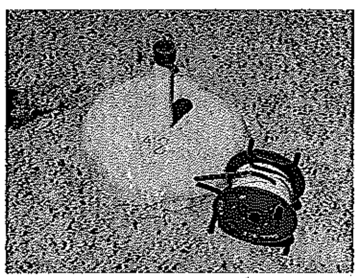


Well A5



Well A6

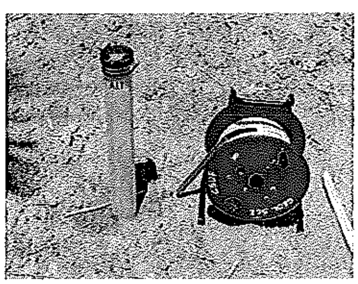
Well A7



Well A8

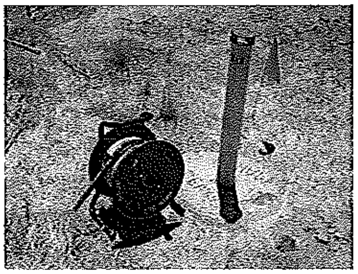
Well A9

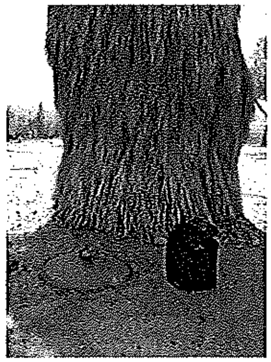
Well A10

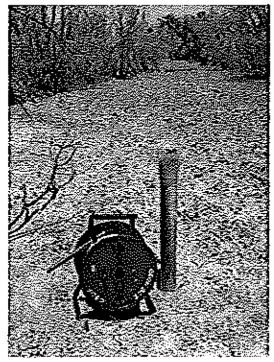


Well A11

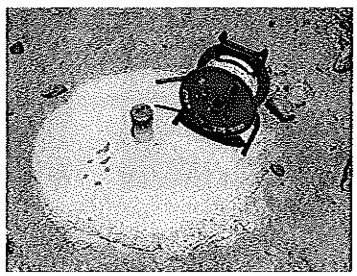
Well A12

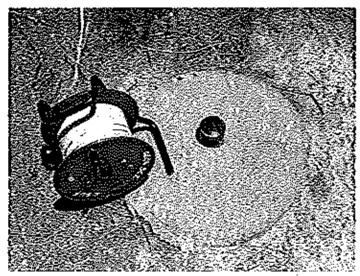

Well A13

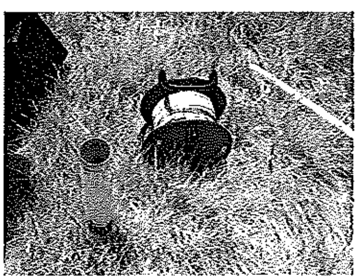

Well A15


Well JW1

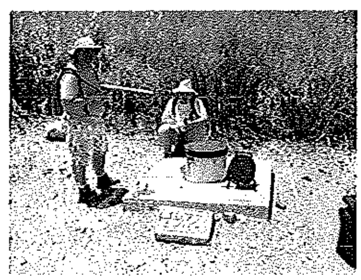

Well JW2


Well JW3


Well JW4


Well JW5


Well MC


Well OPW

APPENDIX C

EVAPORATION PAN, DATA LOGGER, AND WELL PRODUCTION RECORDS

EVAPORATION PAN DATA 1997-1998

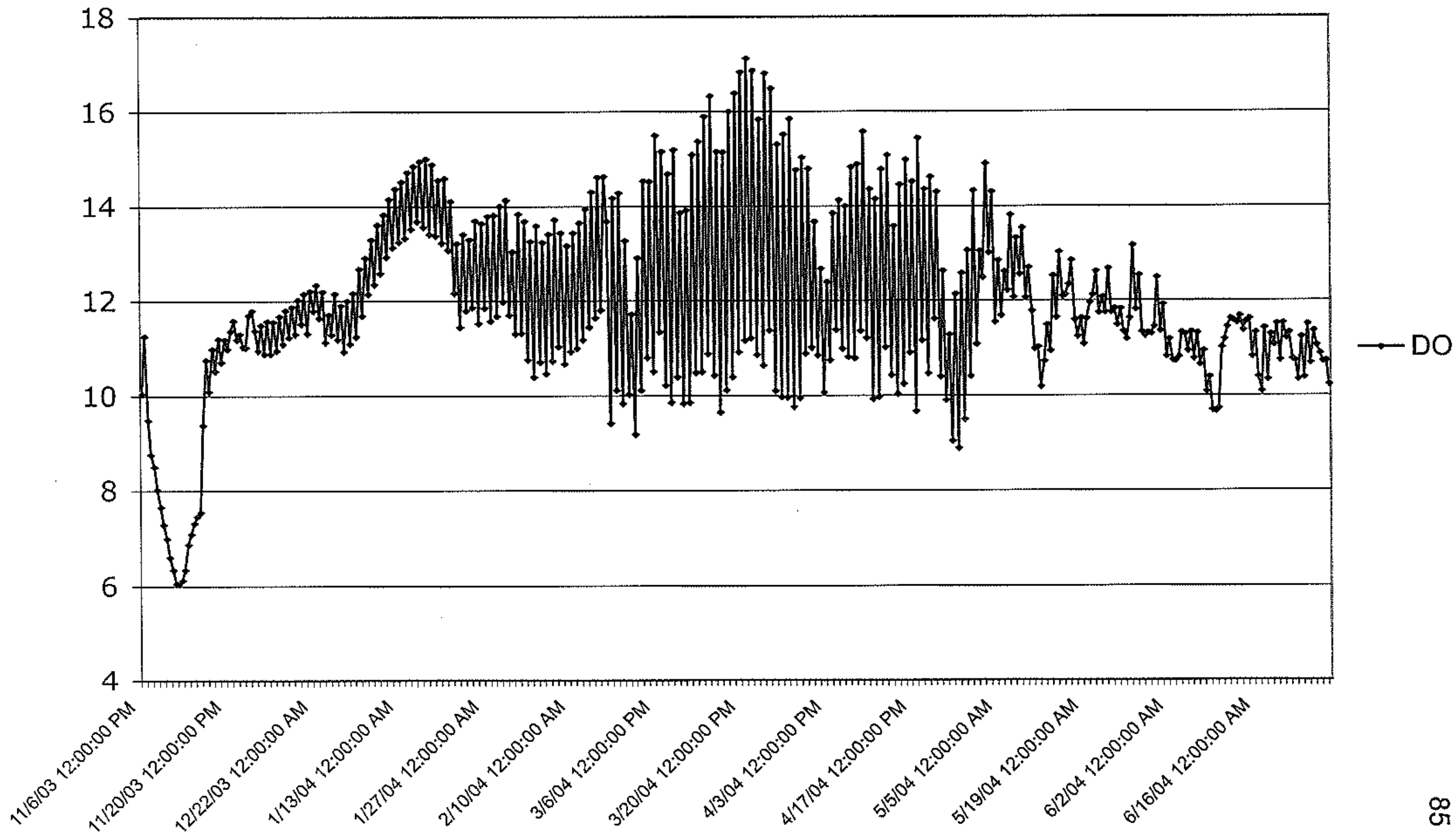
INTERVAL	LEVEL DROP (mm)	RAIN (mm)	NET LOSS (mm)	24 HOUR MEAN (mm)
5/27 - 6/3	83	0	83	11.8
6/3 - 6/10	67	2	69	9.8
6/10 - 6/17	63	2	65	9.3
6/17 - 6/24	93	0	93	13.3
6/24 - 7/1	87	0	87	12.4
7/1 - 7/8	87	0	87	12.4
7/8 - 7/15	90	1	91	13
7/15 - 7/22	83	1	84	12
7/22 - 7/29	73	3	76	10.8
7/29 - 8/5	77	1	78	11.1
8/5 - 8/12	80	0	80	11.4
8/12 - 8/20	95	0	95	11.9
8/20 - 8/26	90	0	90	15
8/26 - 9/3	87	1	88	11
9/3 - 9/9	32	16	48	8
9/9 - 9/16	59	4	63	9
9/16 - 9/23	51	0	51	7.3
9/23 - 9/30	15	17	32	4.6
9/30 - 10/14	81	1	82	5.9
10/14 - 10/21	36	0	36	5.1
10/21 - 11/4	61	0	61	4.4
11/4 - 11/18	51	1	52	3.7
11/18 - 12/2	34	0	34	2.4
12/2 - 12/23	46	1.5	47.5	2.3
12/23 - 1/13	33	2	35	1.7
1/13 - 1/27	28	0	28	2
1/27 - 2/3	13	0	13	1.9
2/3 - 3/30	87	51	138	2.5
3/30 - 4/13	77	0.5	77.5	5.5
4/13 - 4/20	41	0	41	5.8
4/20 - 5/4	104	0	104	7.4
5/4 – 5/12	43	0	43	5.4
5/12 – 5/19	45	0	45	6.4
5/19 – 5/26	52	0	52	7.4
1997-98 Total	2144	103	2247	6.2

EVAPORATION PAN DATA 1998-1999

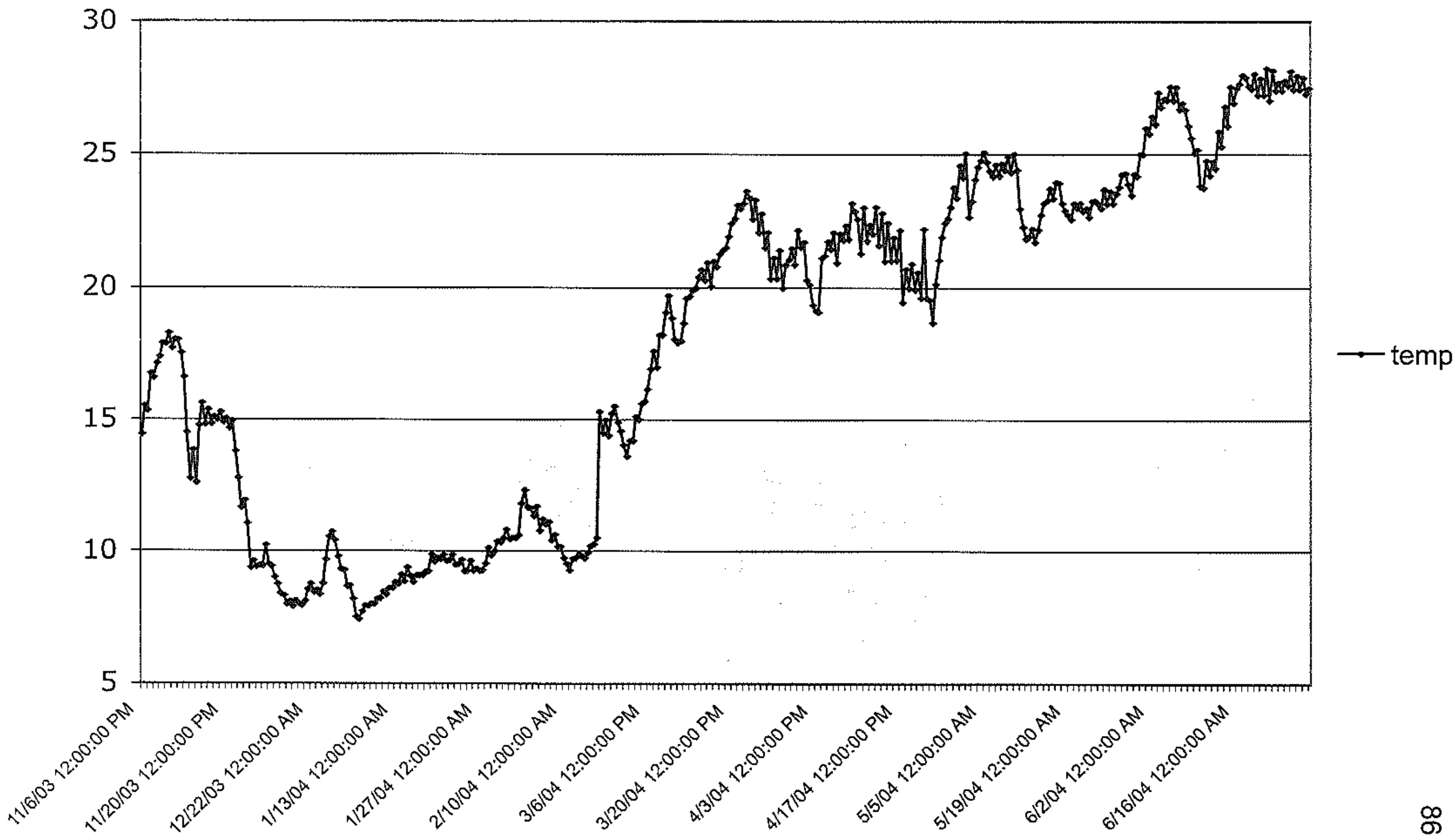
INTERVAL	LEVEL DROP (mm)	RAIN (mm)	NET LOSS (mm)	24 HOUR MEAN (mm)
5/26 - 6/1	59	0	59	9.8
6/1 - 6/9	74	0	74	9.3
6/9 - 6/17	81	0	81	10.1
6/17 - 6/23	68	0	68	11.3
6/23 – 6/30	80	0	80	11.4
6/30 - 7/7	84	0	84	12
7/7 - 7/14	81	0	81	11.6
7/14 - 7/27	125	0	125	9.6
7/27 – 8/3	83	0	83	11.6
8/3 - 8/10	81	0	81	11.6
8/10 - 8/19	81	15	96	10.6
8/19 - 8/26	76	0	76	10.9
8/26 – 9/1	42	18	60	10
9/1 - 9/21	134	8	142	7.1
9/21 – 10/7	102	0	102	6.4
10/7 – 10/19	72	0	72	6
10/19 – 11/1	51	1	52	4
11/1 – 11/16	43	T*	43	2.9
11/16 – 11/30	38	0.5	38.5	2.8
11/30 – 12/14	33	1	34	2.4
12/14 – 1/2	57	0	57	3
1/2 – 1/19	34	0	34	2
1/19 – 2/16	84	7.5	91.5	3.3
2/16 – 3/1	39	0	39	3
3/1 – 3/15	66	0	66	4.7
3/15 – 3/29	73	2	75	5.4
3/29 – 4/14	79	7.5	86.5	5.1
4/14 - 4/21	39	0	39	5.6
4/21 – 5/4	70	7.5	77.5	6
5/4 – 5/24	108	0	108	5.4
1998-99 Total	2137	53.75	2190.75	6

*Trace amount (<0.5mm)

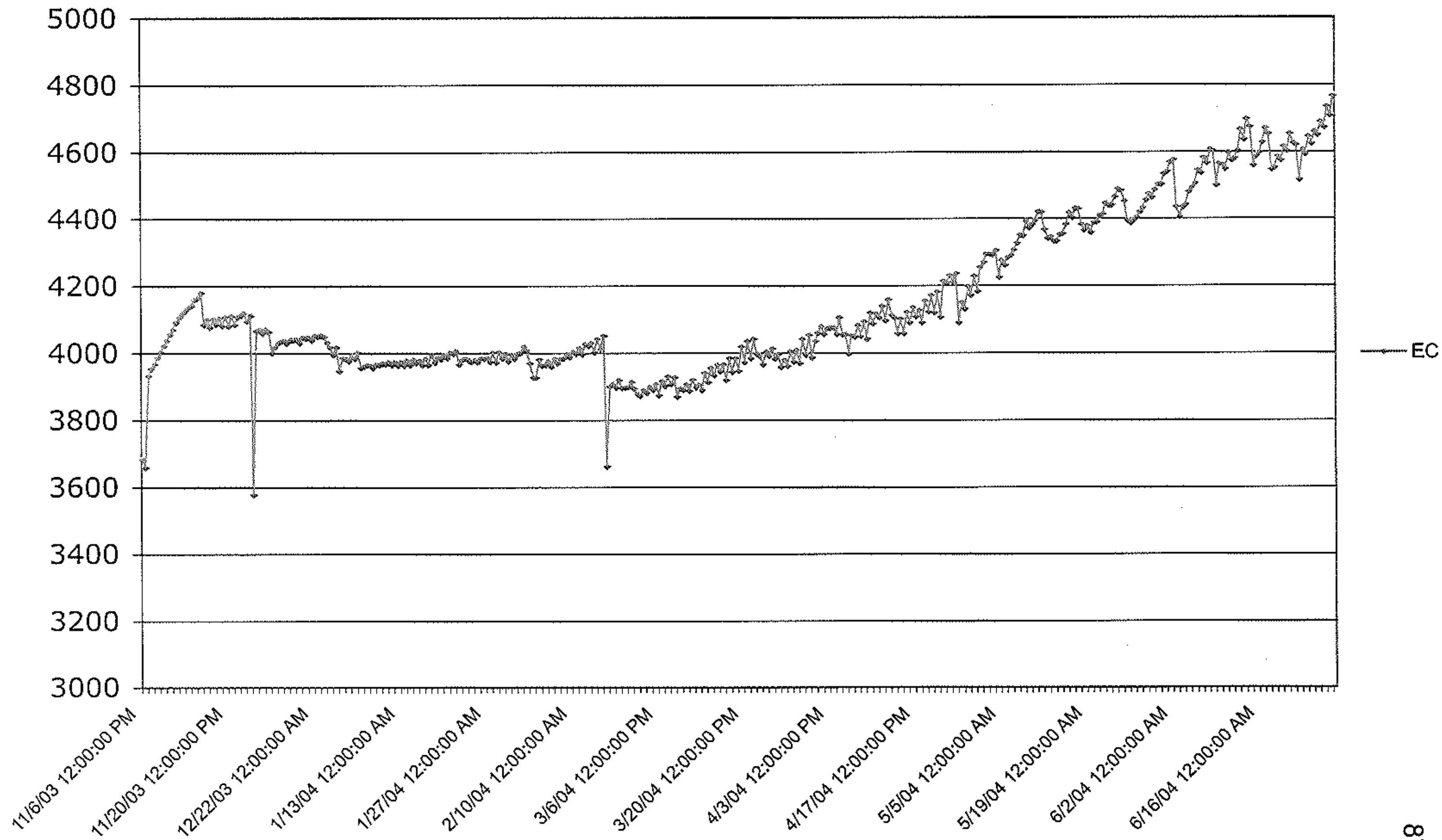
DO of Lake Tuendae



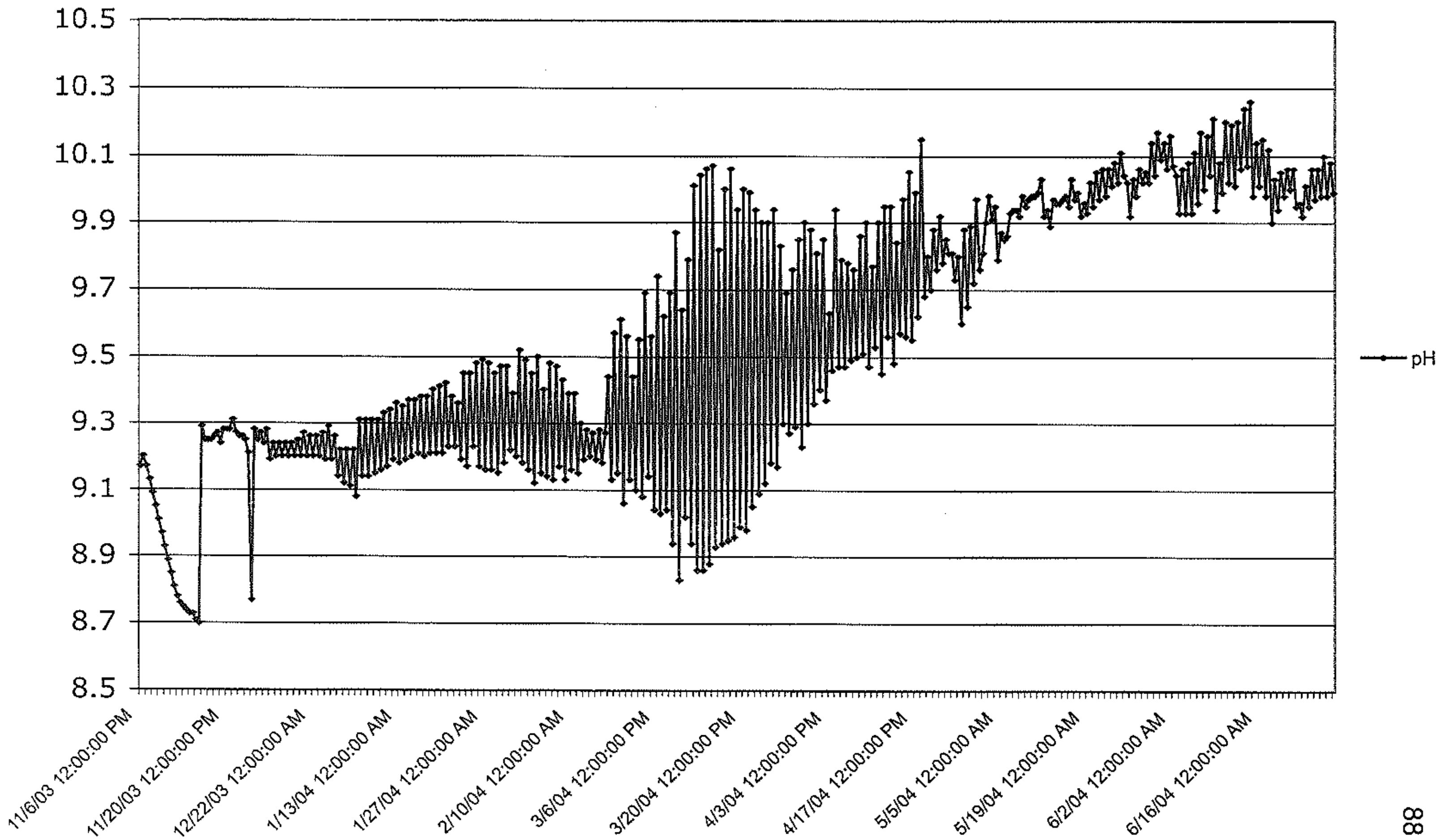
Temperature of Lake Tuendae



EC of Lake Tuendae



pH of Lake Tuendae



Well Production September 2006 to August 2007

MONTH/YEAR	RESERVOIR GALLONS	POOL GALLONS	LAKE TUENDAE GALLONS	TOTAL GALLONS	TOTAL ACRE-FEET
Sep-06	135,000	4,400	1,095,900	1,235,300	3.790
Oct-06	60,000	0	559,727	619,727	1.901
Nov-06	82,500	0	391,950	474,450	1.456
Dec-06	30,000	0	263,250	293,250	0.900
Jan-07	37,500	0	627,900	665,400	2.042
Feb-07	45,000	0	374,400	419,400	1.287
Mar-07	97,500	0	645,450	742,950	2.280
Apr-07	52,500	6,600	883,350	942,450	2.892
May-07	210,000	44,000	1,021,020	1,275,020	3.912
Jun-07	105,000	11,000	1,112,670	1,228,670	3.770
Jul-07	180,000	35,200	1,171,170	1,386,370	4.254
Aug-07	135,000	26,400	1,127,880	1,289,280	3.956
Total Gallons	1,170,000	127,600	9,274,667	10,572,267	
					32.438
Total Acre-feet	3.590	0.392	28.457	32.438	

325,920 conversion factor gallons to acre-feet

APPENDIX D

FIELD MONITORING RECORDS

FIELD MEASUREMENTS 1996

Well or Location	TD TOC	Mar-06 WL TOC	Temp °F	°C	pH	EC µS/cm	TDS ppm	Jun-06 WL TOC	Stick Up
A1	3.74	dry	dry		dry	dry	dry	dry	0.64
A10	9.94	4.37	61	16.1	6.37	>4,000	>2,000	5.16	0.90
A11	10.58	4.96	60.3	15.7	6.24	>4,000	>2,000	5.35	1.45
A12	8.46	5.68	62.9	17.2	6.68	3,784	1,879	dry	1.60
A13	9.74	4.66	59.9	15.5	6.37	>4,000	>2,000	4.89	1.67
A15	11.85	6.12	63.3	17.4	5.91	>4,000	>2,000	8.91	0.10
A2	5.72	4.98	59.9	15.5	7.2	>4,000	>2,000	5.52	0.95
A3	6.58	4.08	64.5	18.1	6.36	3,622	1,800	5.39	0.45
A4	13.5	2.67	60	15.6	6.97	>4,000	>2,000	5.47	1.60
A5	8.12	2.73	54.8	12.7	6.21	>4,000	>2,000	6.31	1.60
A6	7.99	4.8	62.1	16.7	6.25	>4,000	>2,000	6.71	1.50
A7	5.32	4.78	61.1	16.2	6.51	>4,000	>2,000	dry	1.55
A8	4.78	dry	dry	dry	dry	dry	dry	dry	2.30
A9	4.73	4.25	55.6	13.1	6.54	>4,000	>2,000	dry	1.23
JW1	11.96	6.38	63.8	17.7	6.19	>4,000	>2,000	7.09	1.50
JW2	3.62	dry	dry	dry	dry	dry	dry	dry	0.84
JW3	10.12	8.19	65.5	18.6	6.64	>4,000	>2,000	8.35	0.22
JW4	6.34	dry	dry	dry	dry	dry	dry	dry	0.10
JW5	17.32	1.03	60	15.6	6.87	2,980	1,490	2.3	1.35
MC	10.48	4.3	60.9	16.1	6.29	3,443	1,717	5.82	1.50
OPW	22							5.49	
PW	52.25							10.08	
Lake Tuende near Well A9			54.1	12.3	7.51	>4,000	>2,000		
Lake Tuende on south side			53.7	12.1	7.61	>4,000	>2,000		
BLM Pond			55	12.8	7	3,315	1,660		
MC Spring			63.6	17.6	7.05	2,995	1,498		
West Pond									
Arrowhead drinking water			59.4	15.2	6.7	468	230		

FIELD MEASUREMENTS 1996

Well or Location	Aug-06 WL TOC	Temp °F	°C	pH	EC µS/cm	TDS ppm	Sep-06 WL TOC	Temp °F	°C	pH	EC µS/cm	TDS ppm
A1	dry	dry		dry	dry	dry	dry	dry		dry	dry	dry
A10	6.1	86	30.0	6.7	>4,000	>2,000	6.26	82.4	28.0	6.9		
A11	5.67	88.8	31.6	6.6	>4,000	>2,000	5.63	82.8	28.2	7.3	>4,000	>2,000
A12	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
A13	5.17	91.8	33.2	6.5	>4,000	>2,000	5.16	88.1	31.2	6.9	>4,000	>2,000
A15	dry	dry	dry	dry	dry	dry	11.71	dry	dry	dry	dry	dry
A2	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
A3	5.98	89.1	31.7	6.2	3,140	1,540	5.75	84.3	29.1	6.5	>4,000	>2,000
A4	6.9	84.5	29.2	7	>4,000	>2,000	6.98	82.5	28.1	7.1	>4,000	>2,000
A5	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
A6	7.64	88.3	31.3	6.2	3,625	1,820	7.09	81.2	27.3	6.1	>4,000	>2,000
A7	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
A8	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
A9	dry	dry	dry	dry	dry	dry	4.51	dry	dry	dry	dry	dry
JW1	8.57	84.5	29.2	6.2	>4,000	>2,000	8.91	80.8	27.1	6.3	>4,000	>2,000
JW2	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
JW3	8.6	86.7	30.4	6.8	>4,000	>2,000	8.62	86	30.0	7.1	>4,000	>2,000
JW4	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
JW5	1.6	84.6	29.2	6.9	3,069	1,520	1.51	80.9	27.2	7.7	3,120	1,552
MC	6	78.7	25.9	6.1	>4,000	>2,000	5.32	75.5	24.2	6.4	>4,000	>2,000
OPW	5.48	90.9	32.7	7.5	3,481	1,739	5.81	88.8	31.6	7.6	3,525	1,762
PW												
Lake Tuende near Well A9		86.1	30.1	6.9	>4,000	>2,000		74.4	23.6	8.4	>4,000	>2,000
Lake Tuende on south side		88.6	31.4	6.9	>4,000	>2,000		73	22.8	6.9	>4,000	>2,000
BLM Pond		75.7	24.3	6.5	>4,000	>2,000		66.4	19.1	6.8	>4,000	>2,000
MC Spring		78	25.6	6.9	3,080	1,540		73.2	22.9	7.3	3,068	1,536
West Pond							40	75.1	23.9	8.2	>4,000	>2,000
Arrowhead drinking water												

FIELD MEASUREMENTS 1996

Well or Location	Nov-06 WL TOC	Nov-06 Temp °F	Nov-06 °C	Nov-06 pH	Nov-06 EC µS/cm	Nov-06 TDS ppm	Dec-06 WL TOC	Dec-06 Temp °C	Dec-06 pH	Dec-06 EC mS/cm	Dec-06 TDS ppt	Dec-06 DO mg/L	Dec-06 NO3 mg/L
A1	dry	dry		dry	dry	dry	dry	dry	dry	dry	dry		
A10	5.61	74.9	23.8	7.03	>4,000	>2,000	5.43	22.8	-	>20	>10	3.4	
A11	5.33	76.8	24.9	6.38	>4,000	>2,000	5.21	19.8	-	15.18	7.68		
A12	dry	dry	dry	dry	dry	dry	dry	dry	-	dry	dry		
A13	4.98	79.6	26.4	6.46	>4,000	>2,000	4.87	19.5	-	15.45	7.77	6	
A15	8.01	77.1	25.1	6.15	>4,000	>2,000	6.44	22.3	-	>20	>10		0.5
A2	dry	dry	dry	dry	dry	dry	dry	dry	-	dry	dry		
A3	4.63	78.2	25.7	6.63	3,191	1,597	4.01	23.9	-	5.53	2.84	7.9	
A4	6.13	77.8	25.4	6.86	>4,000	>2,000	5.57	20.3	-	>20	>10	1.4	
A5	dry	dry	dry	dry	dry	dry	4.77	19	-	>20	>10		
A6	5.45	75.2	24.0	5.65	>4,000	>2,000	5.21	20	-	6.27	3.2		
A7	5.3	dry	dry	dry	dry	dry	5.05	21.1	-	7.54	3.83		
A8	dry	dry	dry	dry	dry	dry	muddy	dry	-	dry	dry		
A9	4.53	68.3	20.2	6.26	>4,000	>2,000	4.36	16.4	-	12.07	6.12		
JW1	8.74	77.1	25.1	6.24	>4,000	>2,000	8.22	23.7	-	12.54	6.39		
JW2	dry	dry	dry	dry	dry	dry	dry	dry	-	dry	dry		
JW3	8.62	79.8	26.6	6.71	>4,000	>2,000	8.41	22.9	-	5.16	2.63	5.7	
JW4	dry	dry	dry	dry	dry	dry	dry	dry	-	dry	dry		
JW5	1.34	69.3	20.7	7.18	3,027	1,500	1.2	18.9	-	3.22	1.64		
MC	5.33	71.2	21.8	6.31	>4,000	>2,000	5.44	21.7	-	4.63	2.34		
OPW	5.71	78	25.6	7.11	3,465	1,733	5.4	22.78	7.11	3,520	1,773		
PW							12.85	19.83	7.43	3,253	1,625	4.4	
Lake Tuende near Well A9								14.6	-	4.29	2.19		
Lake Tuende on south side													
BLM Pond								15.4	-	3.29	1.75		
MC Spring		68.4	20.2	6.85	2.988	1,494		20.1	-	3.07	1.57	7.3	
West Pond	44												
Arrowhead drinking water													

FIELD MEASUREMENTS 1997

Well or Location	Jan-07 WL TOC	Jan-07 Temp °C	Jan-07 pH	Jan-07 EC mS/cm	Jan-07 TDS ppt	Feb-07 WL TOC	Feb-07 Temp °C	Feb-07 pH	Feb-07 EC mS/cm	Feb-07 TDS ppt
A1	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
A10	5.15	19.1	6.58	>20	>10	4.98	19.8	6.79	>20	>10
A11	4.96	19.4	NM	13.95	7.09	4.92	22.5	6.71	12.99	6.9
A12	muddy	dry	dry	dry	dry	dry	dry	dry	dry	dry
A13	4.78	17.8	6.49	14.19	7.23	4.74	21.4	6.49	12.78	6.48
A15	5.92	18.5	6.01	>20	>10	8.84	20.4	6.24	18.7	9.52
A2	muddy	dry	dry	dry	dry	5.51	23	6.34	>20	>10
A3	3.91	18.8	6.43	4.86	2.46	3.96	21.9	6.78	4.3	2.05
A4	3.71	16.5	7	>20	>10	3.27	17.7	7.22	>20	>10
A5	3.02	13.6	6.76	16.07	8.16	2.87	17.5	6.76	12.75	6.44
A6	4.97	NM	6.39	5.58	2.85	4.93	20.3	6.83	4.48	2.28
A7	4.95	16.2	6.41	6.41	3.26	4.95	20.4	6.82	5.3	2.69
A8	muddy	dry	dry	dry	dry	4.77	22.6	6.57	10.77	5.49
A9	4.22	14.4	6.25	10.62	5.39	4.28	17.8	6.5	11.67	5.9
JW1	7.34	19.6	6.37	13.52	6.87	6.99	21.5	6.38	13.81	7.03
JW2	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
JW3	8.33	22.7	6.87	5.36	2.72	8.28	23.3	7.04	4.94	2.51
JW4	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
JW5	1.11	17.8	7.26	3.66	1.85	1.07	17.5	7.23	3.071	1.53
MC	4.4	15.8	6.47	5.01	2.6	4.34	19.9	6.83	4.89	2.35
OPW						5.48	21.5	7.05	3.58	1.83
PW										
Lake Tuende near Well A9							17.9	7.58	4.18	2.13
Lake Tuende on south side										
BLM Pond		12.8	6.34	3.47	1.74		16.2	6.74	3.23	1.65
MC Spring		16.6	7.14	3.33	1.67		21.8	7.35	3.07	1.56
West Pond						50				
Iron Spring										

FIELD MEASUREMENTS 1997

Well or Location	Mar-07 WL TOC	Mar-07 Temp °C	Mar-07 pH	Mar-07 EC mS/cm	Mar-07 TDS ppt	Apr-07 WL TOC	Apr-07 Temp °C	Apr-07 pH	Apr-07 EC mS/cm	Apr-07 TDS ppt
A1	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
A10	4.47	22.7	6.49	>20	>10	5.03	29.6	6.65	>20	>10
A11	5	23.5	6.2	12.94	6.59	5.22	28.8	6.38	12.82	6.48
A12	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
A13	4.76	24.6	6.3	12.2	6.16	4.99	31.7	6.72	11.87	6.1
A15	5.78	22.2	6.41	11.2	5.73	5.77	23	6.61	9.4	4.75
A2	5.31	23.8	7.24	>20	>10	5.41	33.4	7.43	>20	>10
A3	4.22	24.1	6.4	4.49	2.28	4.95	32	6.53	4.07	2.06
A4	3.13	22.8	7.1	>20	>10	4.02	28.3	7.31	>20	>10
A5	3.09	20.3	6.64	11.96	6.15	4.35	-	6.92	10.54	5.43
A6	5.05	22.6	6.35	4.64	2.37	5.88	29.6	6.33	3.91	1.99
A7	5.02	dry	dry	dry	dry	5.34	dry	dry	dry	dry
A8	4.47	dry	dry	dry	dry	4.94	dry	dry	dry	dry
A9	4.25	24.4	6.61	8.49	4.28	4.34	29.4	6.74	6.82	3.46
JW1	6.56	25.1	6.22	14.38	7.31	6.55	31.2	6.28	14.48	7.47
JW2	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
JW3	8.28	25.1	6.95	5.39	2.77	9.17	33.8	6.88	5.74	2.91
JW4	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
JW5	1.1	24.7	7.09	2.92	1.48	1.29	28.9	7.21	2.88	1.46
MC	4.55	22.2	6.52	3.65	1.86	5.56	28.6	6.59	3.92	1.99
OPW	5.48	24.5	7.02	3.41	1.74	5.9	28.9	6.98	3.25	1.65
PW										
Lake Tuende near Well A9		24.1	7.5	4.16	2.12		28.5	7.84	3.96	2.03
Lake Tuende on south side										
BLM Pond		20.2	6.57	3.6	1.83	WL down				
MC Spring		23.9	7.09	2.92	1.48		32	7.33	2.9	1.47
West Pond	50	25.3	7.98	>20	>10	49				
Iron Spring							29.7	6.61	4.95	2.51

FIELD MEASUREMENTS 1997

Well or Location	May-07 WL TOC	Temp °C	pH	EC mS/cm	TDS ppt	Jun-07 WL TOC	Temp °C	pH	EC mS/cm	TDS ppt
A1	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
A10	5.6	28.7	6.6	>20	>10	6.12	28.2	6.86	>20	>10
A11	5.56	29.5	6.64	13.29	6.75	5.46	27.2	6.5	14.21	7.24
A12	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
A13	5.16	30.1	6.43	13.52	6.83	5.07	27.9	6.54	14.66	7.48
A15	6.67	27.1	6.27	7.15	3.9	8.3	28	6.44	8.99	4.59
A2	muddy	dry	dry	dry	dry	dry	dry	dry	dry	dry
A3	5.48	32.8	6.75	4.72	2.43	5.47	29.1	6.61	2.54	1.31
A4	5.62	27.8	7.41	>20	>10	6.61	26.2	7.63	>20	>10
A5	6.5	23.7	6.58	15.58	7.95	dry	dry	dry	dry	dry
A6	6.63	28.9	6.57	3.83	2.02	7.49	dry	dry	dry	dry
A7	muddy	dry	dry	dry	dry	muddy	dry	dry	dry	dry
A8	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
A9	4.39	dry	dry	dry	dry	4.53	dry	dry	dry	dry
JW1	7.05	29.7	6.26	14.75	7.42	7.66	27	6.4	14.31	7.3
JW2	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
JW3	9.41	dry	dry	dry	dry	8.61	29	6.99	4.79	2.65
JW4	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
JW5	1.47	30.3	7.36	2.88	1.46	1.46	25.5	7.37	3.23	1.65
MC	6.17	25.9	6.31	4.23	2.13	6.02	22.4	6.42	4.89	2.53
OPW	6.04	29.9	7.31	3.3	1.69	5.91	29.3	7.54	3.29	1.66
PW										
Lake Tuende near Well A9		28.8	8	4.15	2.1		26.4	8.47	4.3	2.2
Lake Tuende on south side										
BLM Pond	WL very low									
MC Spring		30.2	7.13	2.82	1.46		25.9	7.27	2.98	1.55
West Pond						40				
Iron Spring										

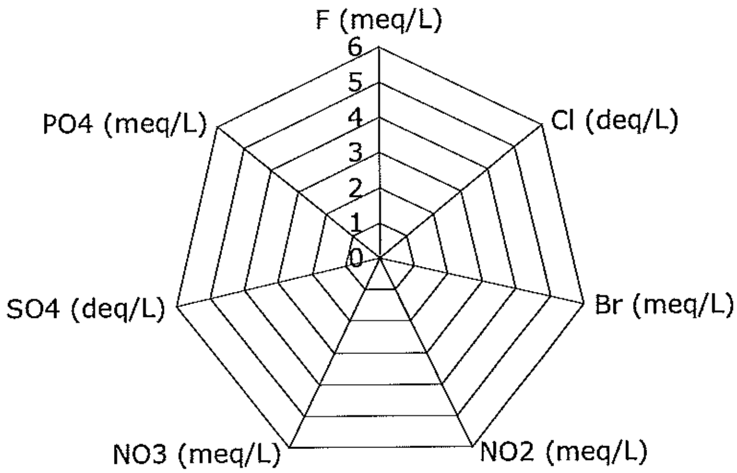
FIELD MEASUREMENTS 1997

Well or Location	Jul-07 WL TOC	Temp °C	pH	EC mS/cm	TDS ppt
A1	dry	dry	dry	dry	dry
A10	6.71	25.6	7.07	>20	>10
A11	5.63	28.2	6.94	13.69	6.98
A12	dry	dry	dry	dry	dry
A13	5.14	29.9	7.56	15.45	7.88
A15	10.15	27.4	6.52	8.62	4.36
A2	dry	dry	dry	dry	dry
A3	5.71	27.3	7.35	3.85	1.97
A4	7.19	26.8	8.16	>20	>10
A5	dry	dry	dry	dry	dry
A6	dry	dry	dry	dry	dry
A7	dry	dry	dry	dry	dry
A8	dry	dry	dry	dry	dry
A9	dry	dry	dry	dry	dry
JW1	8.43	26.4	6.83	13.46	6.86
JW2	dry	dry	dry	dry	dry
JW3	9.03	27.7	7.45	5.32	2.71
JW4	dry	dry	dry	dry	dry
JW5	1.66	29.1	8.05	3.02	1.54
MC	5.76	24.9	6.51	7.98	4.05
OPW	5.97	29	8.06	3.36	1.71
PW	pumping				
Lake Tuende near Well A9		27.7	8.91	4.39	2.24
Lake Tuende on south side					
BLM Pond					
MC Spring		25.2	7.98	3.19	1.71
West Pond	38				
Iron Spring					

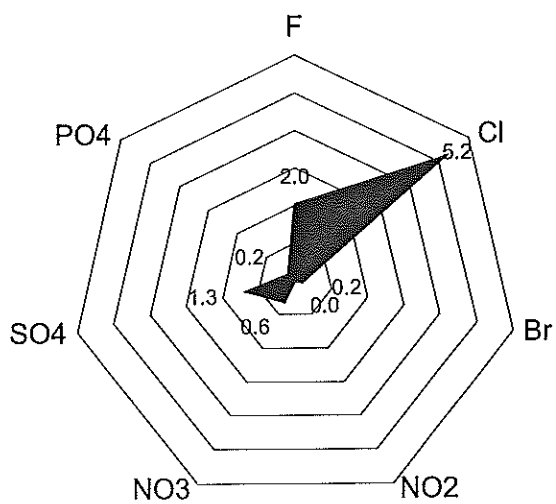
APPENDIX E

2005 ANION ANALYSIS RESULTS

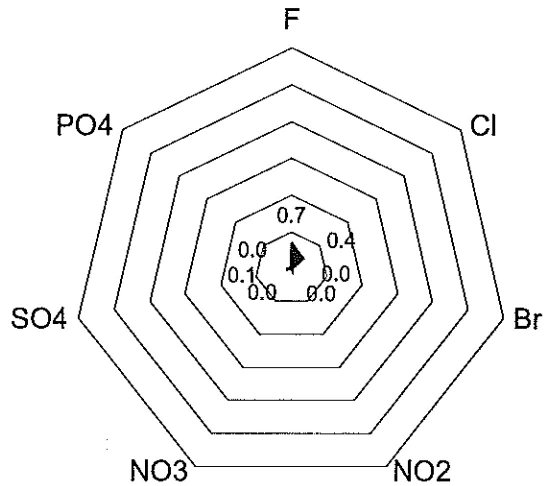
Scale for Anion Graphs



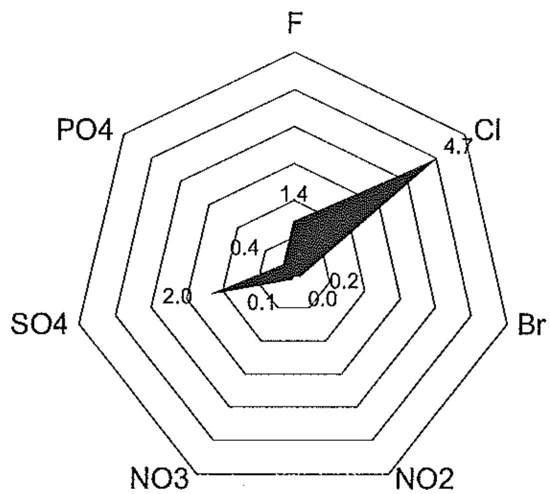
Well A2



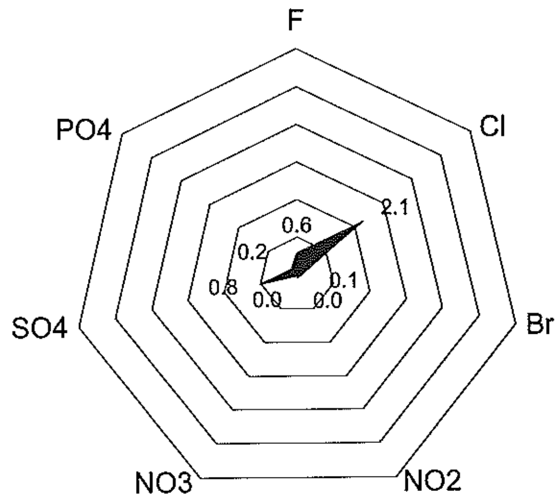
Well A3



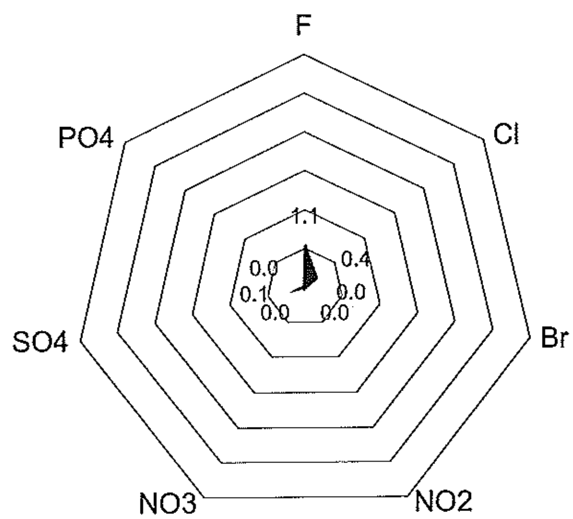
Well A4



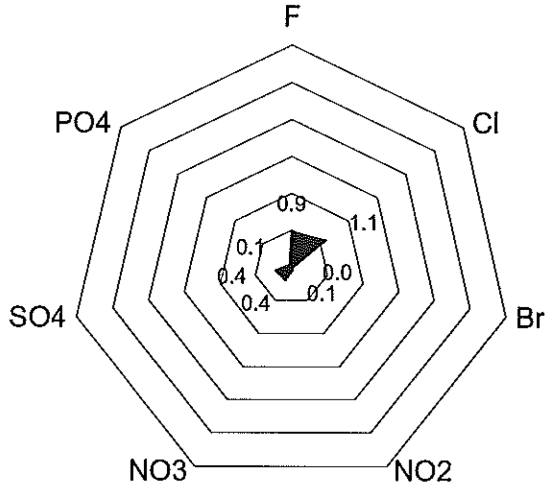
Well A5



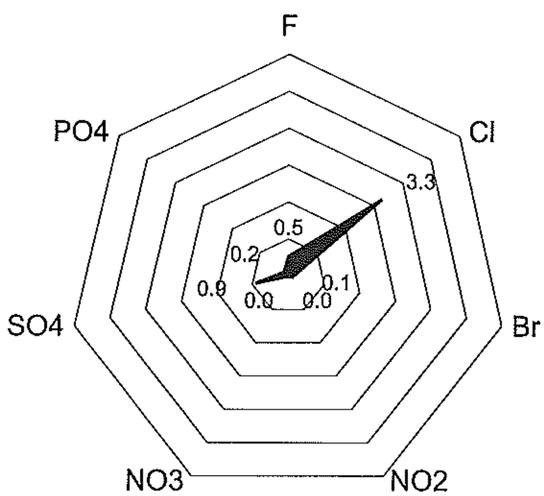
Well A6



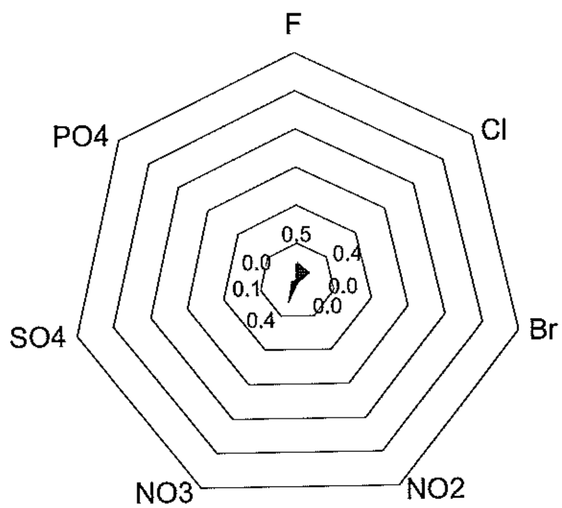
Well A7



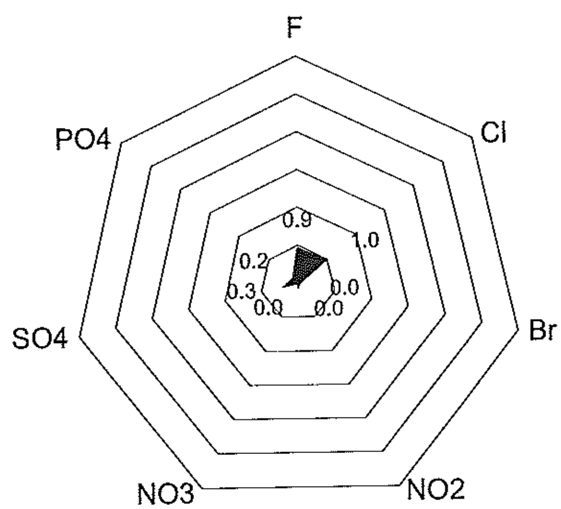
Well A10



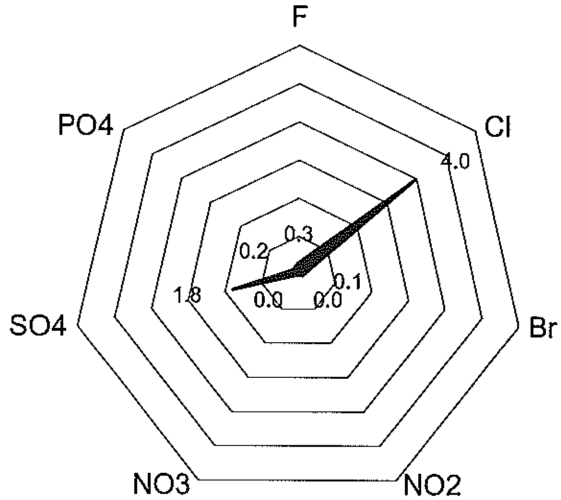
Well A12



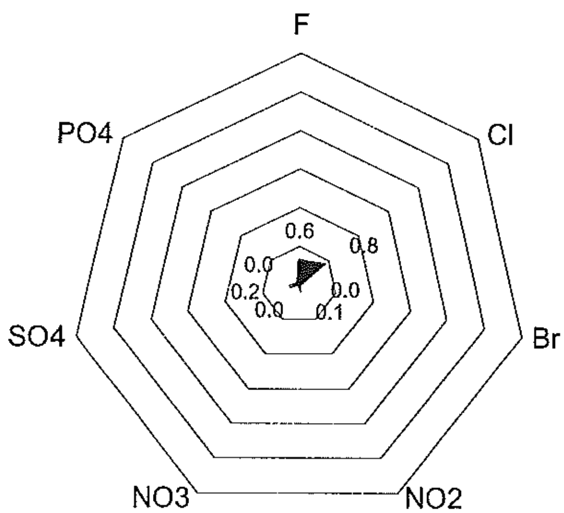
Well A15



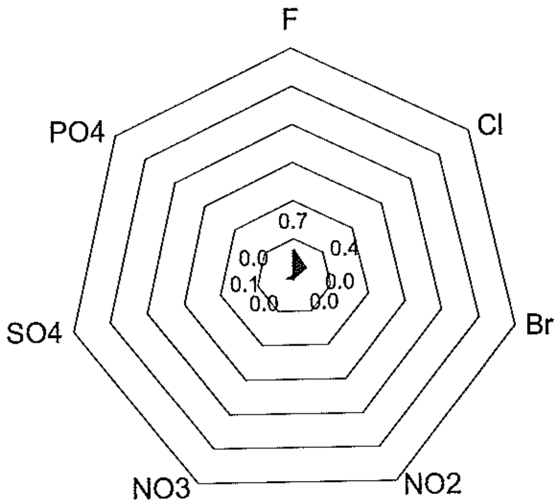
Well JW1



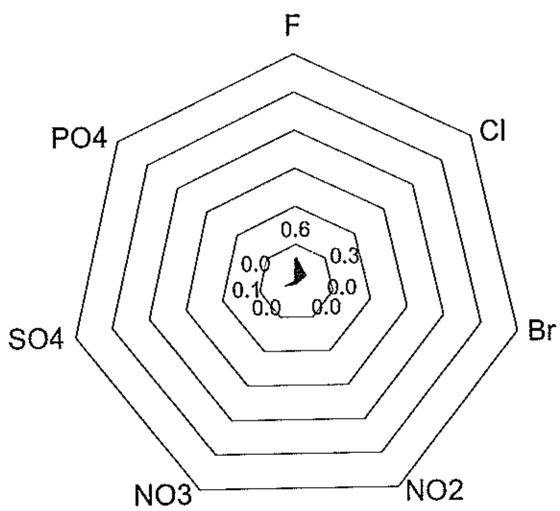
Well JW2



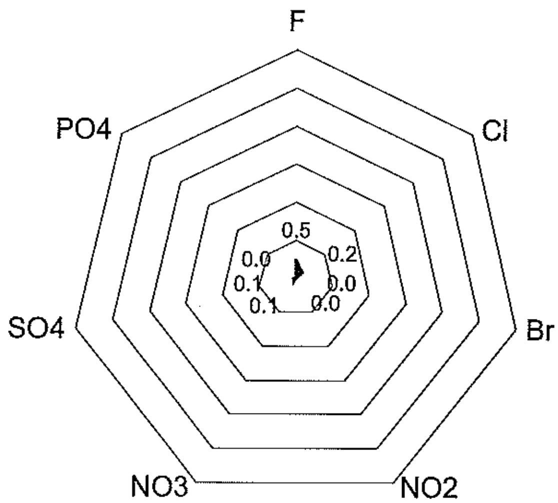
Well JW3



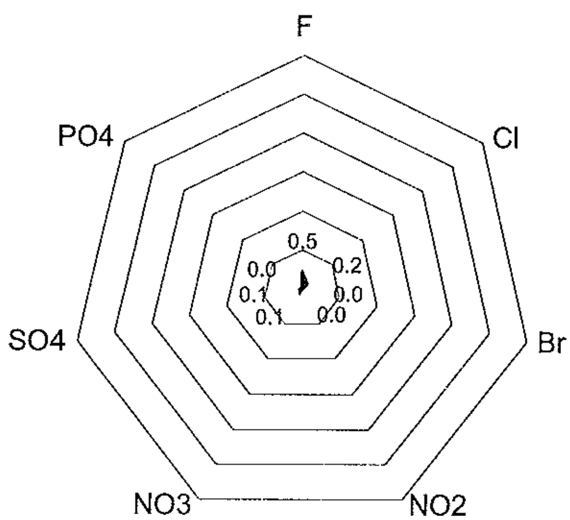
Well MC



Well PW



MC Spring



APPENDIX F

FRACTURE SURVEY DATA

Fracture Measurements

Station #1

	deg	min	sec
N	35	8	27.2
W	116	6	14.8

Strike	Dip	Strike	Dip
N89W	59 S	S88W	62 S
S82W	75 S	N87W	74 S
S74W	72 S	N89W	57 S
S81W	58 S	N52W	46 S
N89W	57 S	N51W	45 S
N85W	60 S	S84W	67 S
N67W	45 S	N49W	45 S
N89W	70 S	N14W	39 S
N84W	70 S	N16W	38 S
N88W	71 S	N52E	60 N
N89W	62 S	N32W	64 S
N64W	47 S	N34W	66 S
N50W	45 S	N13W	71 S
N58W	47 S	N88W	64 S
N88W	69 S	N86W	60 S
N15W	68 S	S82W	52 S
N55E	58 N	S85W	56 S
N54E	55 N	N12W	32 S
N35W	65 S	S88W	62 S
N35W	65 S	S84W	53 S
N12W	72 S	S87W	52 S
N70W	62 N	S84W	51 S
N85W	64 S	S84W	48 S
S84W	56 S	S80W	50 S
S86W	54 S	S84W	44 S
N5W	31 N	N41W	89 S
N89W	60 S	N47W	84 S
S84W	55 S	N50W	89 S
S86W	51 S	N44W	85 S
S84W	49 S	N42W	81 S
S85W	50 S		
S83W	48 S		
S81W	42 S		
N45W	88 S		

Station #2

	deg	min	sec
N	35	8	27.5
W	116	6	16.6

Intrusive Trend
N60W

Station #3

	deg	min	sec
N	35	8	25.7
W	116	6	16.6

Intrusive Trend
S65W

Station #4

	deg	min	sec
N	35	8	28.1
W	116	6	18.3

Strike	Dip
N65E	90
N65E	89 S
N78E	90
N64E	72 S
N63E	70 S
N66E	54 S
N70E	59 S
N69E	64 S
N64E	89 S
N62E	81 S
N83E	90
N62E	72 S
N65E	73 S
N61E	70 S
N68E	62 S
N70E	63 S

Fracture Measurements

Station #5

	deg	min	sec
N	35	8	28.3
W	116	6	17.7

Strike	Dip	Strike	Dip
N68E	52 S	N70E	49 S
N71E	46 S	N72E	48 S
N73E	45 S	N73E	49 S
N73E	42 S	N71E	47 S
N84E	46 S	N84E	46 S
N86E	46 S	N88E	50 S
N80E	42 S	N79E	47 S
N82E	45 S	N82E	45 S
N30E	64 W	N32E	70 W
N70E	45 S	N72E	48 S
N89E	90	N88E	88 W
N82E	51 S	N74E	42 S
N65E	46 S	N64E	46 S
N60E	50 S	N62E	45 S
N57E	52 S	N61E	66 S
N60E	50 S	N62E	48 S
N64E	43 S	N69E	61 S
N60E	55 S	N64E	45 S
N64E	47 S	N70E	40 S
N70E	44 S	N66E	38 S
N64E	33 W	N14W	52 E
N14W	48 E	N18W	64 E
N10W	50 E	N10W	47 E
N14W	59 E	N12W	49 E
N8W	46 E		

Station #6

	deg	min	sec
N	35	8	26.4
W	116	6	17.1

Strike	Dip
N38E	56 S
N35E	50 S
N37E	40 S
N82E	52 W
N78E	52 W
N46E	34 S
N44E	82 W
N5E	75 W
N64E	54 W
N1E	88 W
N38E	50 S
N81E	50 W
N75E	54 W
N5E	89 W
N45E	83 W
N36E	44 S
N78E	52 W
N45E	75 W
N34E	48 S
N32E	49 S
N40E	52 S
N80E	54 W
N76E	50 W
N68E	89 W
N12E	80 S
N65E	78 S
N8W	80 S
N5W	79 S
N39E	50 S
N80E	44 W
N77E	51 W
N5E	81 W
N48E	32 S
N81E	50 W
N10E	68 S

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