# SUMMARY AND EVALUATION OF CIENEGA CREEK SURFACE WATER AND GROUNDWATER MONITORING PROGRAM

## FINAL REPORT

Prepared for

Pima County Flood Control District

Volume I

February 1998

Pima Association of Governments

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# EXECUTIVE SUMMARY

Cienega Creek is an important water, recreation, and wildlife resource located southeast of Tucson, Arizona, in the Santa Cruz River watershed. It is one of the few low-elevation streams in Pima County that exhibit significant perennial flow. Perennial reaches of Cienega Creek support native fish, and the surrounding riparian vegetation provides habitat for a diversity of wildlife. The reach of Cienega Creek between Interstate 10 and a diversion dam east of Vail, Arizona, is the focus of this study. This reach has been designated a Unique Water, which means that it has been classified as an "outstanding state resource water." The Cienega Creek Natural Preserve, which is owned by Pima County Flood Control District (PCFCD), includes most of this part of Cienega Creek.

Pima Association of Governments (PAG), under contract to PCFCD, has monitored groundwater levels, streamflow rates, and the extent of streamflow in the preserve on a monthly basis since 1989. The purpose of the monitoring is to firmly establish baseline hydrologic conditions for comparison purposes, in the event that future groundwater development occurs in the vicinity of the creek, particularly at the proposed Empirita Ranch community, which is to be located directly upstream of the preserve.

Groundwater monitoring was conducted at 13 wells in the project area. Two of these wells were monitored monthly between 1989 and 1997. During this period, no long-term trend toward shallower or deeper groundwater levels was recognized. However, significant seasonal fluctuations were noted, such as rises in groundwater levels during the winter and early spring months, and during the late-summer thunderstorm season. Seasonal groundwater level changes were generally consistent in two or more wells.

Stream discharge was measured at two locations along Cienega Creek between 1994 and 1997. Similar seasonal trends were seen at both sites, with flows significantly increasing during the winter months and in late summer. Between July 1994 and April 1997, the extent of streamflow was monitored on a monthly basis at three intermittent reaches along Cienega Creek. Significant seasonal variations in the extent of flow were observed at all three sites. Seasonal trends in streamflow extent and stream discharge appeared to be closely correlated with trends in groundwater levels at nearby wells. The correlation was less clear with increasing distance between a given stream reach and well, particularly if there were intervening bedrock highs.

Five diurnal studies were conducted between 1995 and 1997. Diurnal variations in groundwater levels were minimal during both the summer and winter months. Diurnal variations in stream discharge were as large as 50% in the summer, but negligible in the winter and early spring.

Streamflow and groundwater level data were compared to meteorological data to estimate the basin's response time to climate trends. Hourly stream discharge and groundwater level data were evaluated to estimate evapotranspiration rates.

A variety of research conducted by students, government agencies, and private firms was reviewed for this project and summarized in this report. Among the studies reviewed was a groundwater flow model that predicted severe impacts from planned groundwater withdrawals at the upstream Empirita Ranch development. PAG's monitoring program appears to be adequate to detect the impacts from this pumpage.

# SUMMARY AND EVALUATION OF CIENEGA CREEK SURFACE WATER AND GROUNDWATER MONITORING PROGRAM

## I. INTRODUCTION

### Background

Cienega Creek is an important water, recreation, and wildlife resource located southeast of Tucson, Arizona (Figure 1). The creek begins at an elevation of approximately 5700 feet in the Canelo Hills, northeast of Patagonia, Arizona, and continues roughly 40 to 50 miles to Pantano Wash, at an elevation of about 3100 feet, near the community of Vail, Arizona. The stream is interrupted, with perennial reaches upstream and downstream of Interstate 10 separated by intermittent and ephemeral reaches. It is one of the few low-elevation streams in Pima County that exhibit significant perennial flow.

Streamflow is diverted at a dam in Section 14 of Township 16 South, Range 16 East, roughly 1.5 miles upstream from Colossal Cave Road (Figure 2). The dam is referred to in this report as the Del Lago Dam, because the diverted water is used by the Del Lago Water Company for irrigation at the Vail Valley development to the northwest. Perennial streamflow in Cienega Creek ends at, or just downstream from, the dam.

In recognition of its value to the state of Arizona, the reach of Cienega Creek downstream from Interstate 10 to Del Lago Dam has been designated by the Arizona Department of Environmental Quality (ADEQ) as a Unique Water, which means that it has been classified as an “outstanding state resource water” (R18-11-112). As a Unique Water, Cienega Creek qualifies for site-specific water quality standards established to maintain and protect the existing water quality (R18-11-112).

In addition, the Arizona Department of Water Resources (ADWR) has issued an in-stream flow right certificate for a designated reach of Cienega Creek between Section 34 and Section 30 of Township 16 South, Range 17 East (McGann & Associates, 1994). The certificate bears a 1983 priority date. The District also has water rights claims to wildlife and recreation uses with 1884 priority dates stemming from the historic Pantano Ranch. The degree of protection these water rights give the stream is subject to ADWR's administrative actions and the Pima County Board of Supervisors' willingness to defend the water rights against future groundwater pumping.

The Cienega Creek Natural Preserve, which is owned by the Pima County Flood Control District and managed by Pima County Parks and Recreation, includes most of the reach of Cienega Creek that has been designated a Unique Water, and all of the reach with an in-stream flow right. The preserve extends from the former headquarters of the Empirita Ranch south of Interstate 10, to Colossal Cave Road (Figure 2). The preserve also includes portions of major Cienega Creek tributaries, such as the lower reach of Davidson Canyon. The presence of surface water combined with riparian vegetation creates a very important

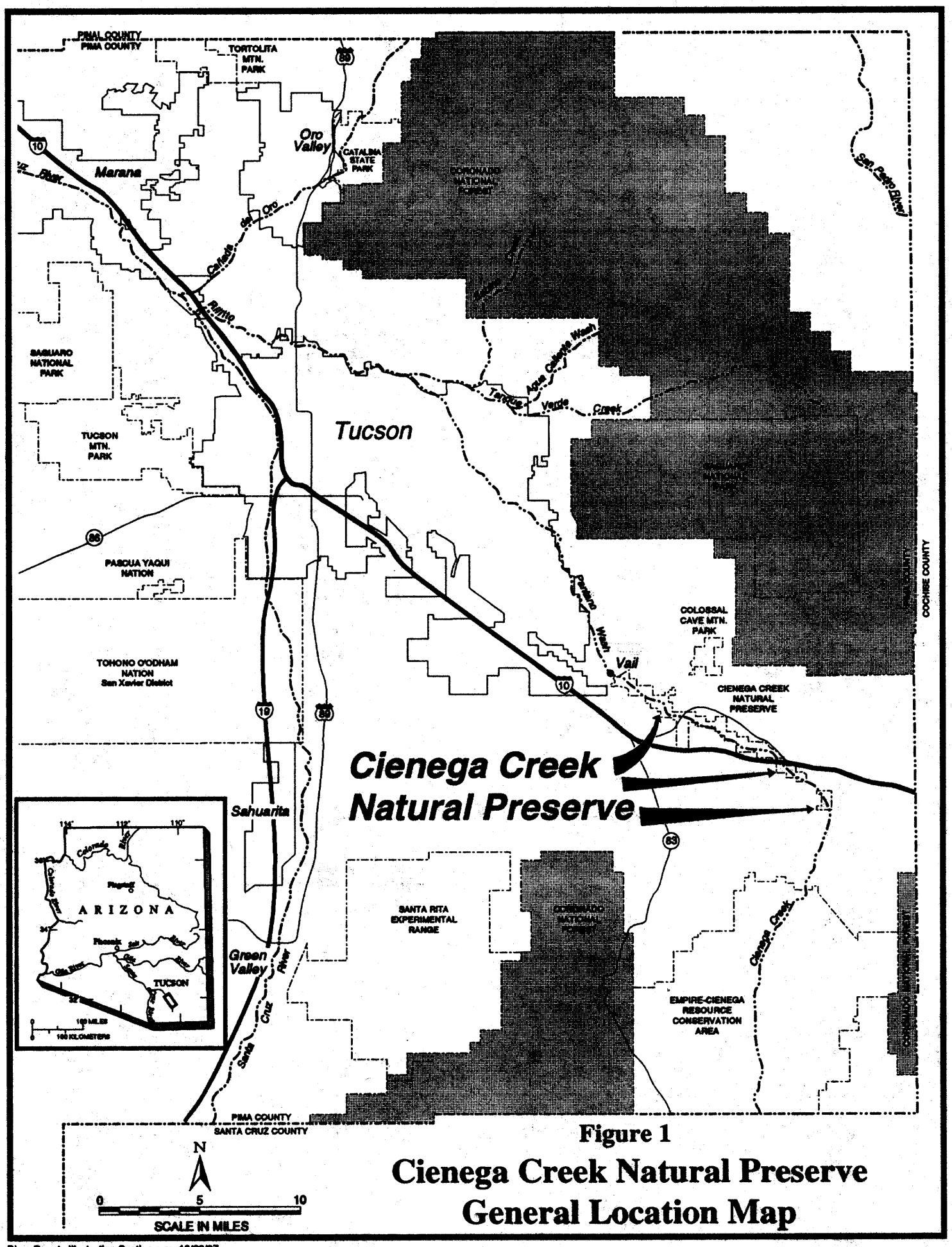



**Figure 1**

**Cienega Creek Natural Preserve General Location Map**

Pima County Illustration Section g.m. 10/22/97

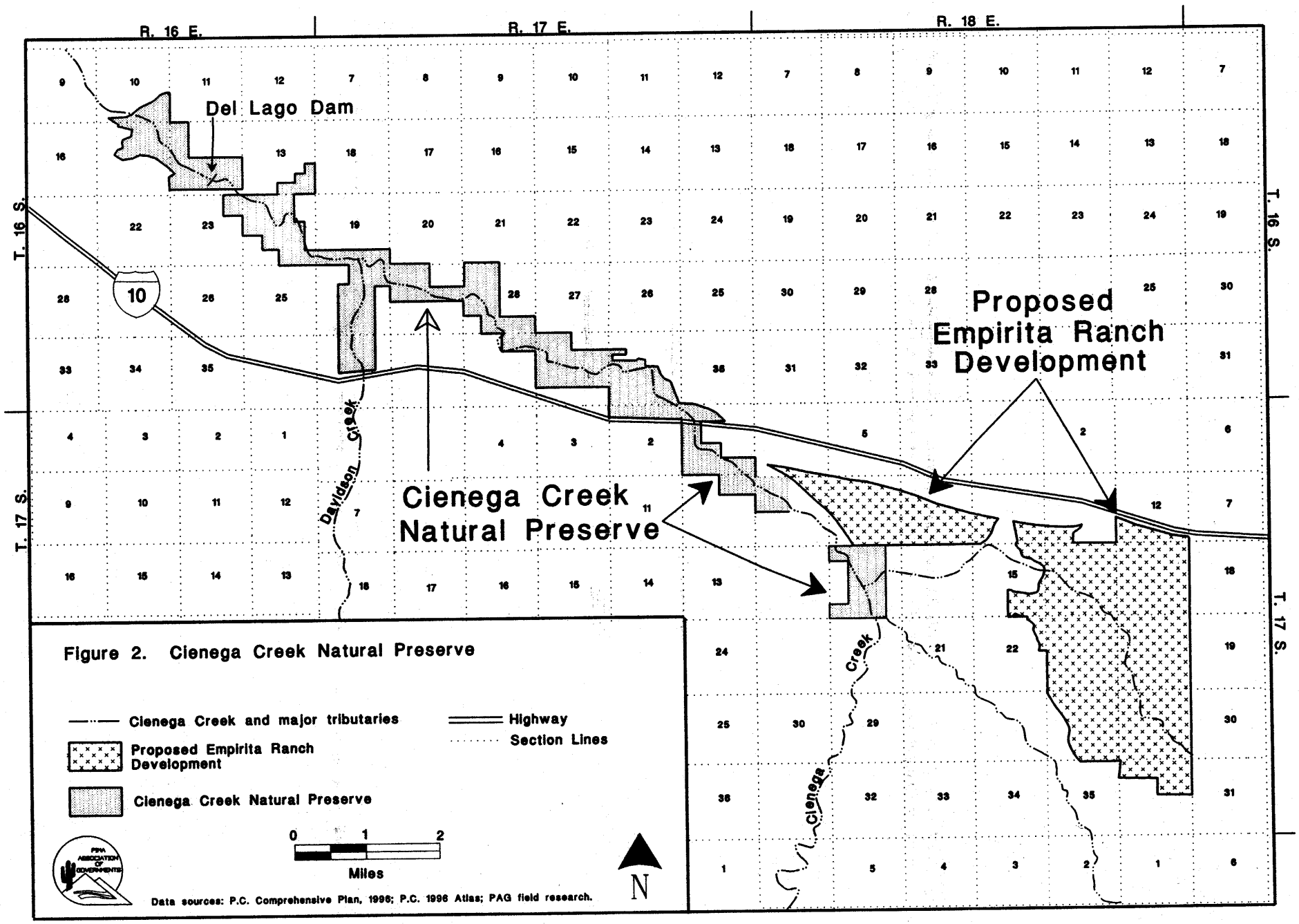



Figure 2. Cienega Creek Natural Preserve

habitat for large and diverse populations of mammals, birds, fish, reptiles, and amphibians. Several special status species are present within the preserve (McGann & Associates, 1994). At the same time, up to 1600 acre-feet of water per year could be withdrawn from the aquifer at Empirita Ranch, pursuant to an acquisition agreement signed by the Pima County Board of Supervisors in 1990.

Because of the potential for future groundwater withdrawals at Empirita Ranch, the creek has been monitored and studied extensively. For example, graduate students at the University of Arizona have completed several theses related to Cienega Creek, and the Arizona Department of Environmental Quality (ADEQ) has monitored the water quality of Cienega Creek as part of its fixed station network monitoring program. Fonseca and others (1990) studied the creek in order to nominate it for Unique Water status, and Pima County Department of Transportation and Flood Control District (1993) studied the creek in order to nominate it for an in-stream flow right. In addition, Pima Association of Governments (PAG) has monitored streamflow and groundwater levels in the preserve in cooperation with Pima County Flood Control District. The purpose of much of the monitoring has been to firmly establish the baseline hydrologic conditions in the lower Cienega Creek watershed, so that any hydrologic impacts due to future development in the watershed can be assessed and mitigated. Also, the monitoring was necessary to quantify in-stream flow rights.

## Purpose

Most of PAG's Cienega Creek monitoring has focused on data collection, with fairly limited interpretation. One purpose of this report is to review PAG's hydrologic data in conjunction with meteorological data, in order to identify long-term and seasonal trends, and to evaluate the surface water and groundwater response to climatological variations.

A second purpose of this report is to review and summarize all of the recent hydrologic studies of Cienega Creek. The summary should be a useful reference for future research locally and statewide.

The final goal of this report is to review the results of groundwater flow models to identify the locations most likely to be impacted by future groundwater withdrawals, and to determine whether PAG's monitoring program is adequate to detect these impacts.

Finally, a goal of this report is to evaluate the results of diurnal groundwater and surface water variations, and other available data, to evaluate the effects of evapotranspiration and, if possible, refine a water budget for the system.

# II. OVERVIEW OF CIENEGA CREEK

## Regional Setting

Cienega Creek, which is tributary to the Santa Cruz River, is located in the Basin and Range physiographic province of the southwestern United States. The Basin and Range province is characterized by a series of broad, relatively flat, alluvial valleys separated by linear, sharply-rising mountain ranges. Most of the mountains and basins trend north-northwest. In southern Arizona, elevations of the mountains vary from less than three thousand feet to more than ten thousand feet above sea level; elevations of the basin floors range from less than 200 feet above sea level in the southwestern corner of the state, near Yuma, to more than 4,000 feet above sea level in the southeastern part of the state.

The basins were formed by horst and graben faulting during the Tertiary period, followed by deposition of locally-derived sediments (Anderson, 1985). The thickness of the basin alluvium generally varies from a few thousand feet to more than ten thousand feet, with the bedrock of the mountains forming impermeable boundaries to the alluvial basin aquifers (Anderson, 1985). The basin aquifers typically consist of Tertiary lower basin fill (deposited during Basin and Range faulting), Tertiary - Quaternary upper basin fill (deposited after Basin and Range faulting), Recent stream alluvium, and pre-Basin and Range sedimentary rocks (Pool, 1985).

The regional climate is arid to semi-arid, with wetter conditions prevailing in the higher mountains. Basin vegetation consists mostly of desertscrub and grasslands, with riparian communities along some rivers and streams. Mountain vegetation ranges from desertscrub, grasslands, and chaparral at lower elevations to conifer and fir forests at the highest elevations. Most precipitation occurs as intense, localized thunderstorms in summer, and regional, gentle rain (and snow at higher elevations) during the winter. In southern Arizona, elevations are progressively lower, and the climate hotter and drier, from east to west.

## Cienega Creek Hydrogeology

The geologic structural controls of the Cienega Creek basin are typical of Basin and Range horst-graben features in southeastern Arizona (Kennard et al., 1988). The basin formed during two periods of sediment accumulation in the Tertiary period. The first started about 30 Ma with deposition of the Pantano Formation, which ranges from strongly indurated conglomerate to poorly indurated mudstone. These deposits were subsequently faulted and tilted during movement on the Catalina-Rincon detachment fault. Movement along this fault was followed by a second period of sediment accumulation. These sediments consist largely of sandstone and conglomerate, and are typically non-indurated to poorly indurated. The younger basin was apparently bounded by north-trending normal faults. The total thickness of basin-fill sediments is up to 1200 feet near the center of the basin (Richard and Harris, 1996).

Four hydrogeologic units are present in the Cienega Creek basin: younger alluvium, basin fill alluvium, Pantano Formation, and bedrock complex. These units were described in a hydrologic report by ADWR (Kennard, et al., 1988). The younger alluvium consists of Quaternary-age alluvial deposits, up to 105 feet thick, of unconsolidated silt, sand and gravel. These deposits are found along the geologic flood plain of Cienega Creek and its tributaries, and form the major aquifer in the lower Cienega Creek basin. The basin fill alluvium consists of Tertiary to Quaternary age, loosely to moderately lithified sedimentary rocks, ranging in grain size from clay to boulders. It is the major water-bearing unit within the Cienega Creek basin,

and acts as a semi-confined aquifer, due to the presence of interbedded, fine-grained material that acts as a confining medium. Few wells have penetrated the entire thickness of this unit, but thicknesses are estimated at less than 1,000 feet in lower Cienega Creek basin to more than 5,000 feet in upper Cienega Creek basin. The Tertiary Pantano Formation consists of moderately to well-lithified sedimentary breccia, fanglomerate, and conglomerate with locally thick gypsiferous claystone deposits. The bedrock complex consists of plutonic igneous rocks of the surrounding mountains, as well as volcanic and sedimentary rocks. The bedrock complex acts as a subsurface hydrogeologic barrier.

The Cienega Creek basin is subdivided at the "Narrows" into lower and upper sub-basins (Fonseca et al., 1990). The Narrows is located south of Interstate 10 in sections 6 and 7 of Township 18 South, Range 18 East, near the confluence of Apache Canyon and Cienega Creek. Perennial flow occurs at the Narrows due to the presence of a bedrock high (McGann & Associates, 1994). Below the Narrows, in the lower basin, the younger alluvium forms the major aquifer, while in the upper basin, the basin fill alluvium constitutes the major aquifer (Kennard et al., 1988). The Cienega Creek Natural Preserve, and the reach of Cienega Creek with a Unique Water designation, are in the lower Cienega basin. Most of PAG's hydrologic monitoring has also been in the lower Cienega basin.

Roudebush (1996) reported aquifer transmissivities in the upper basin ranging from 600 to 40,000 gallons per day per foot (gpd/ft), ten-day storage coefficients in the range of $10^{-2}$ to $10^{-3}$, and a long-term storage coefficient of approximately 0.05, based on pump tests conducted by Harshbarger and Associates (1975). Errol L. Montgomery & Associates (1985) reported a transmissivity of approximately 200,000 gpd/ft and a long-term specific yield of 0.20 for the younger alluvium at the Jungle Road site (section 35 of Township 16 South, Range 17 East) in the lower basin.

Groundwater flows from the mountains to the basin lowlands, roughly parallel to surface water flow (Chong-Diaz, 1995). Based on existing water level contour maps, the general direction of groundwater flow is to the northeast in the upper basin, and to the northwest in the lower basin (Kennard et al., 1988; McGann & Associates, 1994). Groundwater recharge occurs primarily along the slopes of the surrounding mountains, and from infiltration of ephemeral flows along Cienega Creek and its tributaries (Errol L. Montgomery & Associates, 1985).

Depths to groundwater range from more than 300 feet in the outer fringes of the basin, to zero feet along perennial reaches of the streambed (McGann and Associates, 1994).

## Surface Water Hydrology

Streamflow in Cienega Creek consists of base flows and flood flows. Base flows in the lower basin are derived from upstream basin groundwater (Grahn, 1995). Along Cienega Creek, base flows originate at locations with shallow bedrock, where groundwater is forced to the surface, creating perennial streamflow (Chong-Diaz, 1995). In the upper basin, perennial surface flow begins south of the Gardner Canyon confluence and ends downstream from the Narrows (Roudebush, 1996). In the preserve, groundwater first discharges to the surface in section 35 of Township 16 South, Range 17 East, in the vicinity of the Jungle Road crossing. Perennial flow also occurs in some tributaries, including Mattie Canyon, upper and lower Empire Gulch (Roudebush, 1996), and Davidson Canyon. Typical base flows are about 1 cfs to 3 cfs in upper Cienega Creek (Roudebush, 1996), and about 1 cfs to 2 cfs in lower Cienega Creek at the Marsh Station Bridge crossing (PAG, 1996). Base flows in tributaries are significantly lower than the base flows in Cienega Creek.

Flood flows are produced by runoff from significant precipitation events. Historic floods correspond with summer storms from late June through September, and tropical disturbances during September and October. An estimated peak flood flow of 38,000 cfs occurred on August 11, 1958 (USGS data reported by Pima County Department of Transportation and Flood Control District, 1993).

## Water Quality

The water quality of Cienega Creek was described in detail in the Unique Waters Final Nomination Report by Fonseca and others (1990). This report concluded that the water quality of base flows in the reach nominated for Unique Water status met standards for designated uses, including aquatic and wildlife (warm-water). This was confirmed by the 1996 Arizona Water Quality Assessment by ADEQ, which reported that Cienega Creek was in full support of all designated uses, including aquatic and wildlife (warm-water), full-body contact, and agriculture-livestock watering.

The data on Table 1 were taken from Appendix D of the Unique Waters Final Nomination Report. In the unique waters report, the site closest to the Marsh Station Site was labeled SC-7, the site closest to Jungle Road was called SC-8, and the site closest to Del Lago Dam was labeled SC-9. The report also presented analytical results for the following total and dissolved trace substances: Arsenic, Nickel, Boron, Thallium, Cadmium, Beryllium, Chromium, Antimony, Copper, Barium, Lead, Strontium, Manganese, Mercury, Selenium, Silver, Zinc, and Iron. The report did not show any of these trace elements exceeding maximum contaminant levels (MCLs) for safe drinking water.

In addition to the time period covered by the unique waters report, ADEQ continued collecting and analyzing water quality data at SC-7 until 1995 (Lawson, 1997).

## Table 1. Water Quality Data For Cienega Creek (Fonseca et al., 1990)

| SITE | DATE | Ca (mg/l) | Mg (mg/l) | Na (mg/l) | K (mg/l) | HCO3 (mg/l) | SO4 (mg/l) | Cl (mg/l) | F (mg/l) |
|---|---|---|---|---|---|---|---|---|---|
| **SC-7 nr. Marsh Stn** | 5/29/87 | 109 | 32.4 | 56.8 | 6 | 227 | 216 | 13 | |
| | 10/15/87 | 61.4 | 24.4 | 58.1 | 4.9 | 235 | 306 | 20.7 | 0.8 |
| | 11/24/87 | 92.1 | 29.5 | 62.7 | 4.5 | 233 | 300.5 | 17.5 | 1.1 |
| | 1/18/88 | 123 | 32.5 | 60 | 5.77 | 279 | 311 | 17.8 | 0.71 |
| | 4/5/88 | 101.5 | 30.89 | 50.1 | 3.9 | 225 | 361 | 17.96 | 1.14 |
| | 7/20/88 | 70 | 35 | 27.3 | 17.8 | 138 | 108 | 6.7 | 0.31 |
| | 9/21/88 | 93 | 25.9 | 50.1 | 3.9 | 220 | 268 | 15.8 | 0.73 |
| | 11/22/88 | 106 | 26.9 | 50.5 | 4.4 | 206 | 304 | 16 | 0.69 |
| | 1/25/89 | 115 | 31.4 | 56.2 | 3.6 | 229 | 296 | 18.5 | 0.56 |
| | 3/30/89 | 107 | 30.3 | 56.7 | 3.8 | 224 | 308 | 17.8 | 0.72 |
| | 5/23/89 | 129 | 35 | 64.6 | 4.4 | 232 | 327 | 17.8 | 0.82 |
| | 7/25/89 | 130 | 31.7 | 67.8 | 4.8 | 238 | 320 | 18 | 0.77 |
| | 9/24/89 | 126 | 33.2 | 65.1 | 4.3 | 222 | 350 | 17.2 | 0.71 |
| | 11/21/89 | 115 | 33.6 | 69.5 | 3.7 | 227 | 310 | 19.3 | 0.74 |
| | 1/31/90 | 119 | 31.9 | 62.1 | 6.5 | 261 | 349 | 15.6 | 0.72 |
| | 3/27/90 | 117 | 31.7 | 64.5 | 3.8 | 255 | 314 | 14.1 | 0.64 |
| | 5/30/90 | 123 | 33.4 | 61.3 | 3.8 | 213 | 380 | 16 | 0.69 |
| | 7/10/90 | 130 | 32.5 | 60.6 | 5.4 | 232 | 280 | 16 | 0.62 |
| ***AVERAGE*** | | 109.28 | 31.23 | 58 | 5.29 | 227.56 | 300.47 | 16.43 | 0.73 |
| **SC-8 nr. Jungle Rd** | 3/30/89 | 130 | 30.3 | 52.6 | 3.3 | 223 | 307 | 12.9 | 0.77 |
| | 5/23/89 | 116 | 34.6 | 59.6 | 3.8 | 222 | 298 | 12.5 | 0.84 |
| | 7/25/89 | 141 | 29.3 | 61.7 | 5.7 | 236 | 330 | 12 | 0.83 |
| | 9/24/89 | 128 | 33.5 | 57.8 | 4 | 226 | 350 | 11.6 | 0.74 |
| | 11/21/89 | 124 | 33.2 | 59.1 | 3.7 | 244 | 300 | 14.5 | 0.72 |
| | 1/31/90 | 132 | 31 | 52.6 | 5.2 | 307 | 320 | 10.7 | 0.69 |
| | 3/27/90 | 143 | 33.9 | 57.6 | 3.3 | 306 | 308 | 10.3 | 0.64 |
| ***AVERAGE*** | | 130.57 | 32.26 | 57.29 | 4.14 | 252 | 316.14 | 12.07 | 0.75 |
| **SC-9 nr. Del Lago** | 5/23/89 | 135 | 33.7 | 70.8 | 4.8 | 212 | 326 | 18.8 | 0.73 |
| | 7/25/89 | 133 | 31.5 | 75.7 | 5.1 | 240 | 350 | 21 | 0.69 |
| | 9/24/89 | 125 | 33.6 | 69.9 | 4.8 | 228 | 350 | 18.4 | 0.71 |
| | 11/21/89 | 123 | 32.7 | 70.6 | 4.3 | 225 | 300 | 26 | 0.68 |
| | 1/31/90 | 117 | 30.9 | 64.6 | 7.8 | 244 | 344 | 18 | 0.59 |
| | 3/27/90 | 119 | 34.3 | 69.5 | 4.7 | 245 | 155 | 17.1 | 0.59 |
| ***AVERAGE*** | | 125.33 | 32.78 | 70.18 | 5.25 | 232.33 | 304.17 | 19.88 | 0.67 |

Physiography, Climate and Vegetation

The Cienega basin is bounded by the Santa Rita, Whetstone, Canelo, Empire, and Rincon Mountains. Elevations in the watershed, which encompasses an area of 457 square miles (Fonseca et al., 1990), range from less than 3200 feet at the basin outlet, to more than 9400 feet in the Santa Rita Mountains.

The climate of Cienega Creek basin is typical of southeastern Arizona. Rainfall and temperature, and consequently vegetation, vary with land-surface elevation. Cooler, wetter, and more densely vegetated conditions prevail at higher elevations, whereas warm, arid conditions characterize the basin floor. Although long-term temperature data were not collected for the Cienega basin, they were available for the nearby city of Tucson, Arizona. Table 2 presents average monthly climate data for the 1965 to 1995 period of record for Tucson. Cienega basin, which is located at higher elevations than Tucson, probably had slightly lower temperatures and greater amounts of precipitation than those recorded at Tucson. Precipitation in the area tends to occur as summer "monsoon" thunderstorms, and more regionally extensive winter storms. Cienega Creek climate data and trends are discussed in more detail in Section 3.

**TABLE 2. TUCSON, ARIZONA CLIMATE DATA**

| Month | Avg. Daily Max. Temp (F) 1965-94 | Avg. Daily Min. Temp (F) 1965-94 | Avg. Precip. (in.) 1965-94 | Possible Sunshine (%) Clear to Partly Cloudy Days, 1961-90 | Relative Humidity (%) 11:00 A.M. 1961-90 | Avg. Wind Speed (mph) 1961-90 |
|---|---|---|---|---|---|---|
| **January** | 64.5 | 36.8 | 0.89 | 80 | 41 | 7.9 |
| **February** | 67.8 | 39.3 | 0.83 | 82 | 35 | 8.1 |
| **March** | 73.0 | 43.0 | 0.75 | 86 | 30 | 8.6 |
| **April** | 81.1 | 48.8 | 0.34 | 92 | 21 | 8.9 |
| **May** | 89.7 | 56.3 | 0.21 | 93 | 17 | 8.8 |
| **June** | 99.1 | 65.8 | 0.25 | 93 | 16 | 8.7 |
| **July** | 99.3 | 73.0 | 2.18 | 78 | 32 | 8.4 |
| **August** | 96.8 | 71.5 | 2.20 | 80 | 38 | 7.9 |
| **September** | 94.1 | 66.1 | 1.31 | 86 | 32 | 8.3 |
| **October** | 84.9 | 54.5 | 0.72 | 88 | 30 | 8.2 |
| **November** | 73.1 | 43.5 | 0.75 | 85 | 33 | 8.1 |
| **December** | 65.3 | 37.7 | 1.06 | 79 | 40 | 7.8 |
| ***Annual*** | *82.4* | *53.0* | *11.49* | *85* | *30* | *8.3* |

Source: National Oceanic and Atmospheric Administration, 1995.

The Cienega Creek basin is in a transitional zone between the Sonoran and Chihuahuan Deserts, and includes plants from each (McGann & Associates, 1994). Upland vegetation on rolling hills above the Cienega Creek floodplain consist of Sonoran desertscrub, Chihuahuan desertscrub and semi-desert grassland with pine and oak woodland in the upper portions of the watershed. Riparian woodlands flank the perennial and ephemeral portions of the stream, and include velvet mesquite, Goodding willow, Arizona ash, hackberry, and Fremont cottonwood (Fonseca et al., 1990).

Fish and Wildlife

The presence of water and lush riparian vegetation provide valuable habitat for large and diverse populations of fish and wildlife. In addition, the riparian corridors along Cienega Creek and several tributaries provide connections between the Cienega Creek Natural Preserve and large, protected natural areas such as the Rincon Mountains and Santa Rita Mountains.

Perennial reaches of Cienega Creek support populations of native fish, including the Longfin Dace, and, in upper Cienega Creek, the Gila Chub and Gila Topminnow. The Gila Chub and the Gila Topminnow are special status species. Both have been listed by the Arizona Game and Fish Department as threatened, and the United States Fish and Wildlife Service has listed the Gila Topminnow as Endangered. The creek is also home to special status species of frogs and snakes, and many species of birds and mammals. Mammals observed in the natural preserve include coyote, gray fox, collared peccary, bobcat, mule deer, and a variety of bats. Birds likely to be present include great blue herons, turkey vultures, hawks, owls, jays, doves, and many others. No special status bird or mammal species are known to be present in the preserve, but the endangered Southwestern Willow Flycatcher could be present (McGann & Associates, 1994).

Land Uses and Potential Impacts

Land uses in the Cienega Creek basin include grazing, recreation, transportation corridors, mining, agriculture, and private residences. The land is a mix of federal, state, county, and privately-owned land (Fonseca et al., 1990). Despite the variety of land uses in the area, most of the basin is relatively undisturbed compared to the adjacent Tucson basin. In fact, much of the basin is part of an open-space network that includes the Cienega Creek Natural Preserve, the Empire-Cienega Resource Conservation Area, Saguaro National Park, and the Coronado National Forest (McGann & Associates, 1994).

Although much of the area is publicly-owned open space, significant tracts of private land are present in the basin, including several thousand acres northwest of the natural preserve and 15,000 acres southeast of the preserve. Planned communities have been proposed for both of these holdings (McGann & Associates, 1994). In addition, ASARCO has proposed the acquisition of more than 10,000 acres of Coronado National Forest land for new mining operations in the Santa Rita Mountains, in exchange for privately-held lands throughout the state that would be acquired by the U. S. Forest Service (ASARCO, 1995; PAG, 1996a). A site plan (Fonseca, 1996) indicates that the mine would be located near the headwaters of Davidson Canyon, which is a major tributary to Cienega Creek.

Various existing and future land uses, if not properly managed, could adversely affect the quality and quantity of surface water, groundwater, riparian vegetation and wildlife habitat in the Cienega Creek basin. Of particular concern is that increased groundwater withdrawals due to future development will lower water tables in the basin. If water tables drop, perennial streamflow could be diminished, and riparian vegetation that relies on shallow groundwater could be jeopardized. This type of impact has occurred in many locations in southern Arizona, including the adjacent Tucson basin.

Other potential land-use impacts include the possible degradation of water quality in the basin. For example, the transportation corridors present a potential threat from spills of hazardous materials transported through the area on railroads and Interstate 10. In addition,

mining activities are a potential source of turbidity and heavy metals in runoff, and agricultural areas are potential sources of nitrates and pesticides. Finally, various recreational activities could damage riparian vegetation, adversely affect wildlife, and possibly degrade surface water quality.

Cienega Creek Management

Careful management of resources and human activities will be required to ensure that high-quality perennial streamflow and riparian habitat are preserved in the Cienega Creek basin. The most significant preservation effort has been the establishment of the Cienega Creek Natural Preserve. Also contributing to the potential for successful preservation of the creek are the designation of Unique Water status, the certification of an in-stream flow right, establishment of the Empire-Cienega Resource Conservation Area, and the presence of National Park and National Forest land in the basin.

The Cienega Creek Natural Preserve was established in 1986 to preserve riparian habitat, provide for natural flood storage, and maintain natural groundwater recharge. The preserve encompasses 3,979 acres of land along Cienega Creek that are owned by Pima County Flood Control District and managed jointly by the District and Pima County Parks and Recreation Department. The management plan for the preserve has three principal objectives: to preserve and protect the perennial streamflow in the creek; to preserve and protect the existing natural riparian community along the stream corridor; and to provide opportunities for public use of the preserve for recreation, education, and other appropriate activities. Specific actions identified in the management plan include, among many others: restrictions or prohibitions on livestock grazing, mining, and motor vehicle use; limitations on the number of visitors; continued monitoring of water quality, streamflows, and groundwater levels; encouragement of research regarding groundwater/surface water relationships and water needs of riparian habitat; monitoring, reporting, and remediation of potential sources of contaminants within and adjacent to the preserve; and acquisitions of additional lands along the creek or adjacent to the preserve (McGann & Associates, 1994).

Cienega Creek's designation as a Unique Water should help protect the water quality of the stream. According to state surface water rules (R18-11-107 and R-18-11-112), existing water quality of a Unique Water shall be "maintained and protected," and degradation will not be allowed. In addition, site-specific water quality standards can be adopted for a Unique Water. In the case of Cienega Creek, site specific standards for pH, temperature, dissolved oxygen, total dissolved solids, and turbidity have been adopted. The Unique Waters designation might have other, less tangible benefits as well. For example, the designation might increase public awareness of the stream's value and prompt more diligent efforts to monitor and manage activities with the potential to degrade water quality.

The certificate of in-stream flow rights was granted by the Arizona Department of Water Resources (ADWR) to Pima County Flood Control District in December 1993. The Certificate of Water Right No. 89090.0000 is for a designated reach of Cienega Creek within the natural preserve between Section 34 and Section 30 of Township 16 South, Range 17 East (McGann & Associates, 1994). An in-stream flow right is a legal entitlement to use surface water within a specified reach of a stream channel for fish, wildlife or recreational uses. Depending on how the state interprets the connection between groundwater and surface water flows, the in-stream flow right could protect a designated flow from depletion by new water users, including situations where new upstream uses, developments, or diversions could threaten the existing flows. Because the use must be non-consumptive, the water remains in the stream for

downstream users, and other right holders are generally not affected (Kulakowski and Tellman, 1990). For Cienega Creek, the designated beneficial use associated with the in-stream flow right is wildlife use (Pima County Department of Transportation and Flood Control District, 1993).

The Empire-Cienega Resource Conservation Area (RCA) was established in June 1988. The RCA encompasses approximately 75,000 acres, and includes most of the Cienega Creek watershed upstream of the preserve. Much of the land in the RCA is currently owned by the Arizona State Land Department, but the federal Bureau of Land Management (BLM) holds most of the grazing leases for the area and is responsible for overall resource management. The BLM has adopted an interim management plan for the RCA which will remain in effect until a more thorough inventory of resources can be conducted and a long-term management plan can be prepared. Appropriate management of the RCA can help ensure a continuous supply of high-quality water and protection of existing natural resources in the area (McGann & Associates, 1994).

The presence of National Forest and National Park land along the margins of the watershed also aids in the preservation of Cienega Creek. In most cases, these lands are less likely than private lands to experience extensive urban or suburban development. As noted above, however, some of the National Forest land near the headwaters of Davidson Canyon, in the Rosemont Ranch area, may be transferred to private ownership for development of a new mine.

# III. CLIMATE DATA

Precipitation Data

As part of this investigation, PAG compiled and analyzed precipitation data for fourteen stations in the Cienega Creek area. Monthly precipitation data were collected, when available, between January 1989 and May 1997 for each of the stations. Figure 3 shows the locations of the climate stations.

Precipitation data for the Cienega basin and surrounding areas indicated that the annual precipitation in Tucson varied, on average, less than one inch from the annual precipitation in the lower Cienega basin, near Interstate-10 (Figure 4). In contrast, Patagonia, Arizona, which is similar in elevation to the upper Cienega basin, received approximately 6.5 inches more precipitation per year than Tucson. The higher elevations of the watershed, represented by a station in the eastern Santa Rita Mountains, received an average of almost 10 inches more rainfall annually than Tucson.

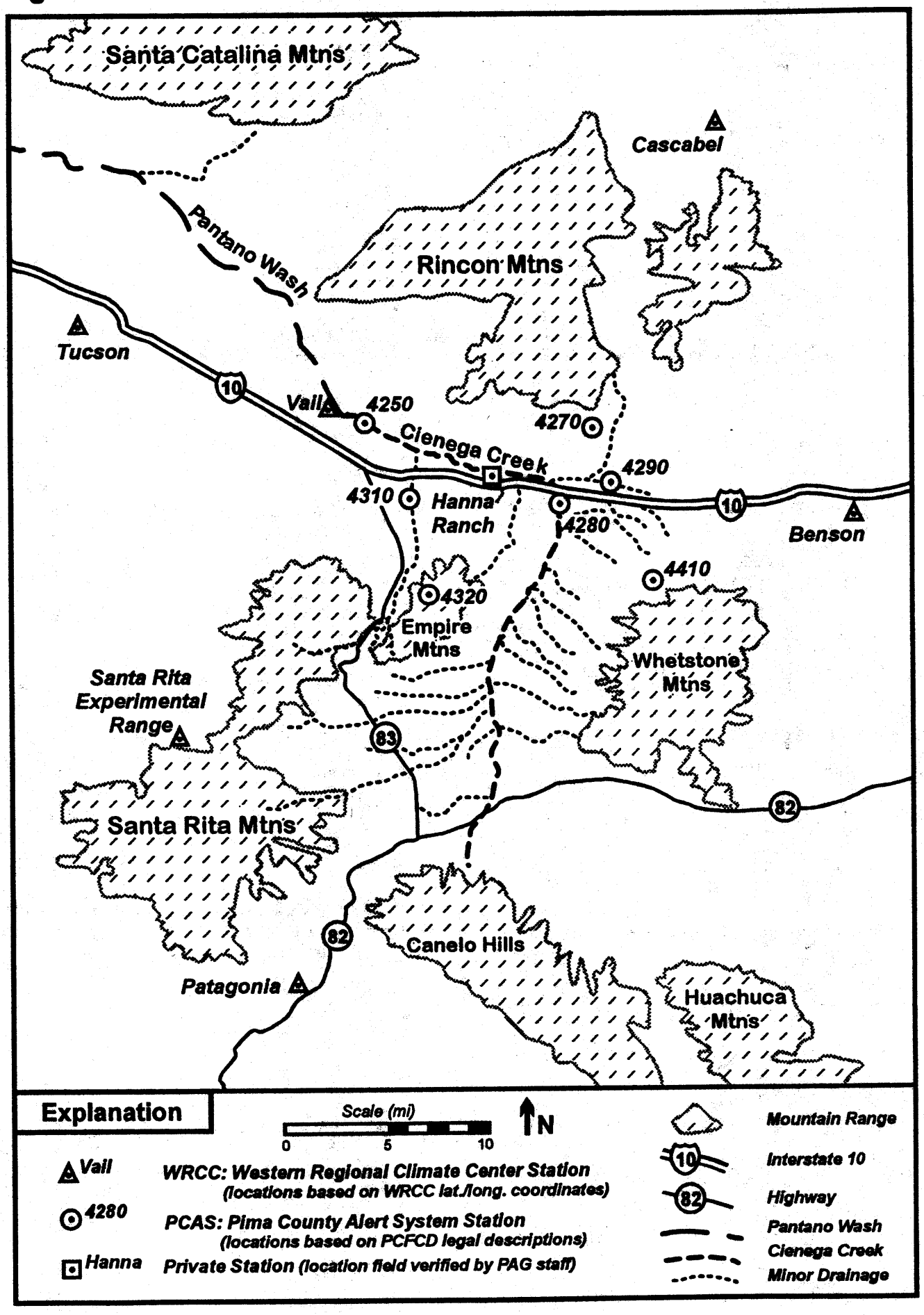
Seasonal precipitation patterns were consistent with the rest of southeastern Arizona. Most of the precipitation occurred as intense, localized summer thunderstorms and regional winter rains and snow. Although summer storms tend to be localized in this region, the data collected by PAG indicated that the storms were sufficiently widespread to affect monthly precipitation totals throughout the entire Cienega Creek basin area.

PAG received data for six regional weather stations (Figure 3) from the Western Regional Climate Center (WRCC) of the Desert Research Institute in Reno, Nevada. These data were collected as part of the National Climate Data Center's data collection system. The regional climate stations included: Tucson International Airport; Vail 6 North; Santa Rita Experimental Range; Benson 6 South; Cascabel; and Patagonia. No data were available for dates after January 1997 for any of these stations. Tables showing representative data are presented in Appendix A.

The WRCC data were collected at three types of stations. The station in Vail consisted of a recording rain gage, the Tucson International Airport station was measured by National Weather Service personnel, and the other stations were Cooperative Stations of the National Weather Service, where volunteer observers reported the data. Each of the files provided by the WRCC listed the maximum allowable number of missing days as five.

Precipitation information was also collected from the Pima County Alert System (PCAS) for seven stations located adjacent to, or within, a few miles of Cienega Creek (Figure 3). These precipitation gages were numbered according to the Pima County system. Four of the gages were located along Cienega Creek or its tributaries: near Vail, Arizona (gage 4250); in lower Davidson Canyon (gage 4310); near the Interstate-10 crossing of Cienega Creek (gage 4280); and near the Cochise County line (gage 4290). Three stations were located at higher elevations: in the southern foothills of the Rincon Mountains (gage 4270); at Haystack Mountain in the northern Whetstone Mountains (gage 4410); and in the Empire Mountains (gage 4320).

## Figure 3: Climate Stations referenced in this Study



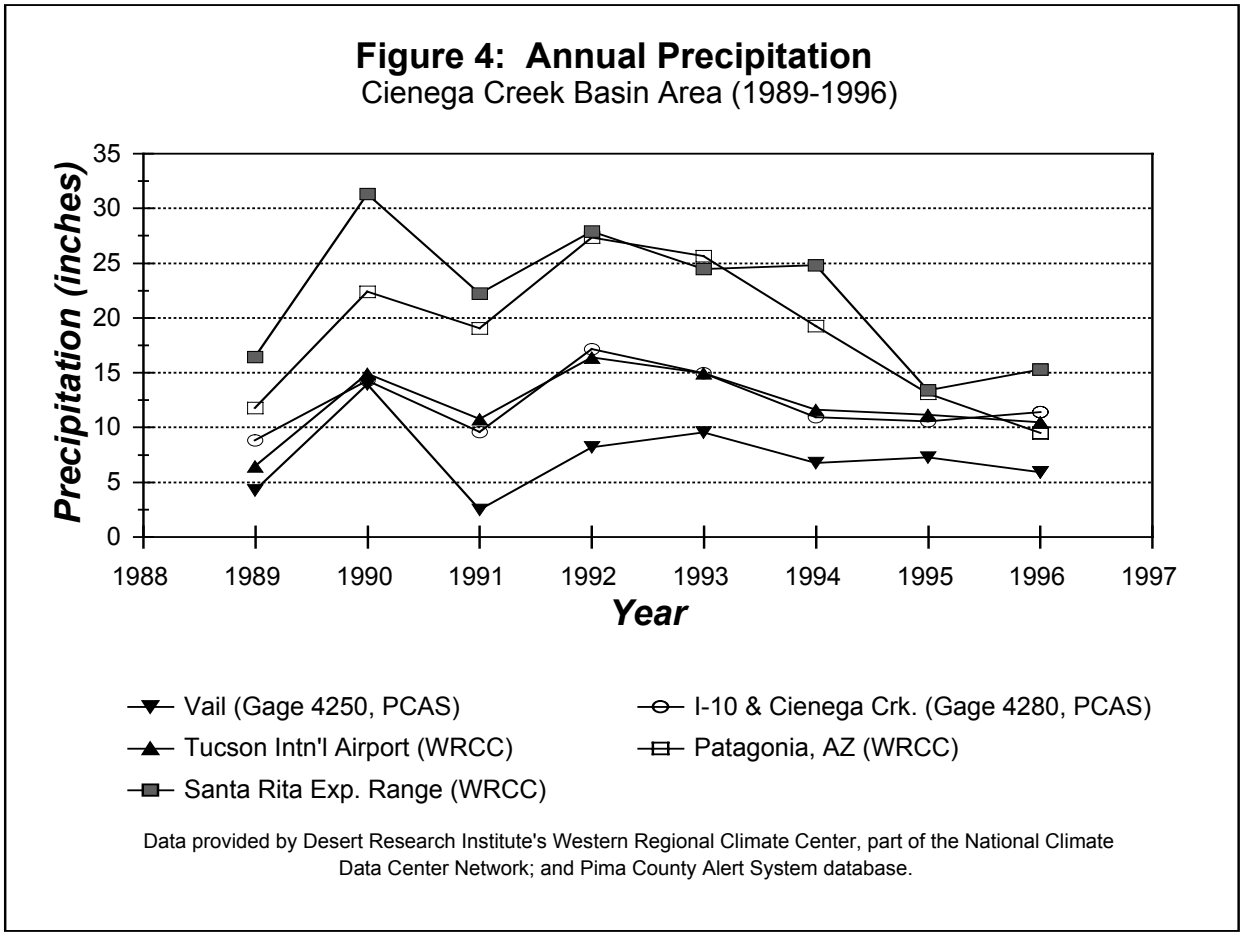
The Pima County Alert System (PCAS) data probably slightly under-represented the precipitation received near the Pima County stations. PAG's review of the data showed that significant amounts of data were missing from the files. In some cases, Pima County provided PAG with the supplemental precipitation data that consisted of the cumulative precipitation for several days, weeks, or as much as three months. If only a few days of data were missing, PAG entered the cumulative precipitation amount on the last day of the hiatus. When cumulative data were provided for days spanning several months, PAG split the precipitation evenly between all of the months. Even with the additions made by PAG, the data were incomplete. Also, precipitation at PCAS stations was measured using "tipping gages." These gages measured precipitation in 0.04 inch increments. Any precipitation that measured less than this amount was not recorded, resulting in an underestimate of rainfall.

Monthly precipitation data were also received from the Hanna Ranch, a private residence along Cienega Creek. These data showed trends similar to those seen at other stations located along Cienega Creek. However, several increases in monthly precipitation totals were not recorded by the Hannas even though they were recorded at neighboring stations.

Precipitation data were analyzed on an annual and monthly basis to determine precipitation trends over time. Figure 4 shows the annual precipitation at selected stations in the lower Cienega basin, and in surrounding areas. The amount of precipitation falling in the lower basin was generally between 10 and 17 inches per year. However, the two stations closer to the upper basin (Santa Rita and Patagonia) recorded more precipitation on average. This graph also shows that generally lower amounts of precipitation have been received in the area since 1993. The upper basin area received less rainfall in 1995 than any year since 1989. Based on data for the Vail gage, the lower basin received the least amount of annual precipitation in 1991.

Precipitation data were also analyzed on a monthly basis to determine seasonal and regional variations in rainfall. Peaks were uniformly seen during the late summer months and during the winter months. Late summer rainfall generally occurred in a few large-magnitude events, whereas winter precipitation generally occurred as more frequent, smaller-magnitude events. Although summer thunderstorms tend to be localized, trends in monthly precipitation totals were fairly consistent at various stations in and around the Cienega basin.

PAG used a Quattro-Pro spreadsheet to correlate precipitation data from various stations throughout the study area. This analysis compares two sets of data to determine a correlation coefficient between -1.0 and 1.0, where a value of 1.0 is a perfect positive correlation, a value of -1.0 is a perfect inverse correlation, and a value of 0 indicates that there is no correlation. This analysis showed that data from the Tucson International Airport correlated very well with data from the Pima County Alert System gage 4280 at the intersection of Cienega Creek and Interstate 10. Data from both of these stations also correlated well with data from other stations throughout the study area. As a result of this analysis, PAG determined that precipitation data from PCAS gage 4280 would be used to represent precipitation for comparison to groundwater and surface water trends. Selected correlation coefficients are presented below.



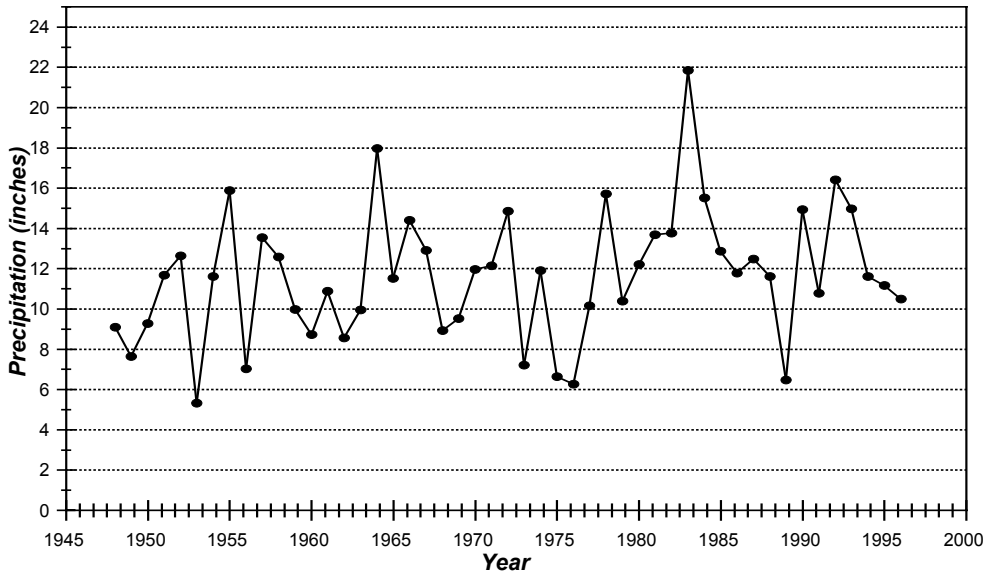

| Precipitation Stations | Correlated Precipitation Stations | Correlation Coefficient |
|---|---|---|
| Tucson International Airport (WRCC) | Gage 4280: I-10 & Cienega (PCAS) | 0.93 |
| Tucson International Airport (WRCC) | Patagonia, AZ (WRCC) | 0.86 |
| Tucson International Airport (WRCC) | Benson, AZ (WRCC) | 0.77 |
| Patagonia, AZ (WRCC) | Santa Rita, AZ (WRCC) | 0.86 |
| Gage 4280: I-10 & Cienega (PCAS) | Gage 4410: Haystack Mtn (PCAS) | 0.54 |
| Gage 4280: I-10 & Cienega (PCAS) | Patagonia, AZ (WRCC) | 0.81 |

Comparison of Precipitation Data to Historical Averages

Figure 5 presents annual precipitation totals for the Tucson International Airport (TIA) between 1948 and 1996. The average annual precipitation for this period was 11.6 inches. The average annual precipitation at TIA during PAG's Cienega Creek monitoring program, which began in 1989, was 12.1 inches. Precipitation totals for individual years in this period ranged from significantly below to significantly above the long-term average.

**Figure 5: Annual Precipitation for Tucson Int'l Airport**

1948-1996




Data provided by Desert Reseach Institute's Western Regional Climate Center, part of the National Climate Data Center Network.

Drought Indices

Figure 6 shows Palmer Drought Indices for southeastern Arizona during PAG's Cienega Creek monitoring program. Palmer Drought Indices quantitatively compare the actual amount of precipitation recorded in a particular area to the average amount of precipitation expected in that area during the same specified period. The variables used to calculate the indices include precipitation, potential and actual evapotranspiration, infiltration of water into the soil zone, and potential runoff (Palmer, 1965).

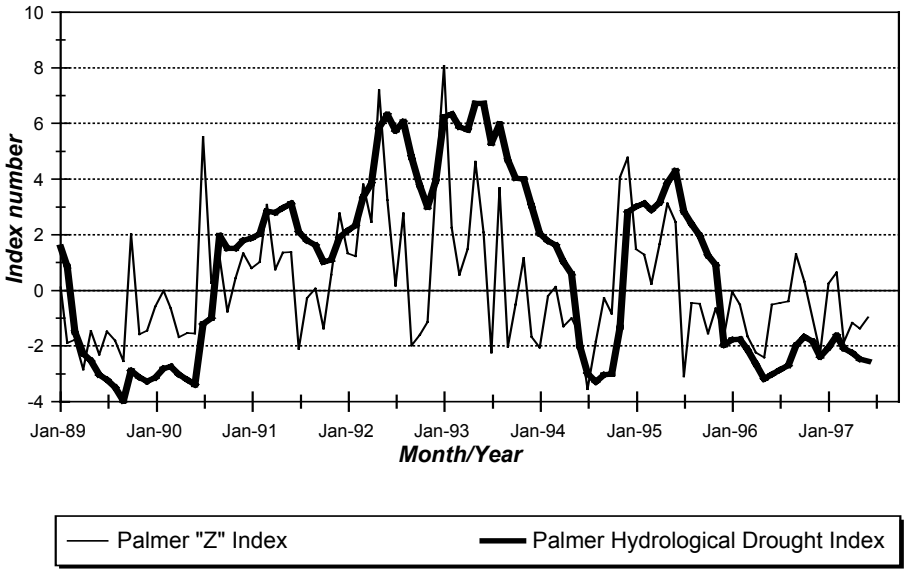
Data for several types of Palmer Drought Indices were available from the National Oceanic and Atmospheric Administration's National Climate Data Center for the entire United States going back to 1895. In the National Climate Data Center's database, each state was divided into regions dependent upon consistent general climatic characteristics. The Cienega Creek basin was in Region 7 of Arizona, which includes Pima, Cochise, Graham, and Greenlee counties.

PAG obtained data for two types of drought indices from the National Climate Data Center: the Palmer Hydrological Drought Index (PHDI), and the Palmer "Z" Index (ZNDX). Data were also available for the Palmer Drought Severity Index (PDSI), which is widely used in the United States. However, the PHDI more-closely reflects the availability of water such as soil moisture, streamflow, etc., when a dry or wet spell is ending. Once there has been a change in the weather, this index responds slowly because it is more closely linked to water storage.

The ZNDX is very sensitive to unusually wet or dry months even during periods of extended wet or dry spells, and is often described as the "Moisture Anomaly Index" (NCDC, 1997). This index can respond to a period of above-normal precipitation even during a long drought period. It is the best index for assessing short-term moisture deficiencies. Each monthly ZNDX value

**Figure 6: Palmer Drought Indices for Southern Arizona**

January 1989 - June 1997




Data provided by the National Oceanic and Atmospheric Administration's National Climatic Data Center-Climate Visualization (CLIMVIS), Climate Division, Drought Database.

expresses the relative departure from "normal" of the general moisture climate for that particular month.

The conditions represented by the values of the Palmer indices are listed on Table 3. Based on the PHDI indices shown on Figure 6, the region has experienced moderate to extreme drought conditions at least three times during PAG's monitoring program: 1989-90; 1994; and 1996-97. This represents roughly 30% of the monitoring period.

**Table 3: Conditions represented by values of the Palmer Drought Severity Indices**

| PHDI | Description of Conditions | ZNDX |
|---|---|---|
| > 4.0 | Extreme wetness | > 3.5 |
| 3.0 to 3.99 | Severe wetness | 2.5 to 3.49 |
| 1.5 to 2.99 | Mild to moderate wetness | 1.0 to -2.49 |
| 1.49 to -1.49 | Near normal | 0.99 to -1.24 |
| -1.50 to -2.99 | Mild to moderate drought | -1.25 to -1.99 |
| -3.0 to -3.99 | Severe drought | -2.0 to -2.74 |
| < -4.0 | Extreme drought | < -2.75 |

(NCDC, 1997)

# IV. GROUNDWATER MONITORING

Description of Monitoring Program and Methodology

PAG began monitoring groundwater levels in the lower Cienega basin in 1989. The monitoring program included a total of 13 wells, but only two of these wells, the Del Lago #1 well and the Cienega well, were monitored regularly for the entire period from 1989 to 1997. Water level trends at these two wells are discussed in the following section in more detail than water levels at the other eleven wells, which were only monitored during portions of this period. Table 4 provides location and construction information for all the wells. The well locations are also shown on Figure 7, and available drillers' logs are included in Appendix B.

Between 1994 and 1997, the groundwater monitoring program included monthly groundwater-level measurements at five wells. PAG monitored two of these wells (Del Lago #1 and Cienega) and obtained water level data for the other three (Jungle, Empirita #1, Empirita #2) from caretakers working and/or residing within the preserve.

PAG used a consistent methodology for all of the measurements. The same electric sounder was used for each measurement, and PAG attempted to make all of the measurements during the first week of each month, on the same days that the streamflow measurements and observations were made. In addition, PAG attempted to make the measurements at roughly the same time of day each month. Also, measurements were made from a consistent measuring point at each well. The height of the measuring point was subtracted from the depth-to-water measurement to get the corrected depth to water below land surface. Water table elevations were calculated by subtracting the corrected water level depth from the land surface elevation. Most land surface elevations were based on USGS topographic maps. The measuring points and sources of land surface elevation data are described in Appendix C, which includes all of the water level data collected by PAG. PAG's sounder is labeled in metric units; the data were converted to feet for reporting purposes.

PAG did not supervise the personnel who measured water levels at the Jungle, Empirita #1, and Empirita #2 wells. For purposes of this report, it was assumed that the data PAG obtained for these wells was accurate, and that errors associated with inconsistencies, if any, in methodology used in these measurements were negligible.

A private consulting firm, Errol Montgomery and Associates, also measured groundwater levels at a number of wells in the lower Cienega basin (Errol Montgomery and Associates, 1993). The Montgomery monitoring program began in 1983 and continued until 1992. PAG reviewed Montgomery data for three wells, Cienega, Jungle and Empirita #2, and included these data in this report. However, the Montgomery water level data reported herein are approximate, because the water levels were interpreted from graphs included in the Montgomery monitoring report for calendar year 1992 (Montgomery and Associates, 1993).

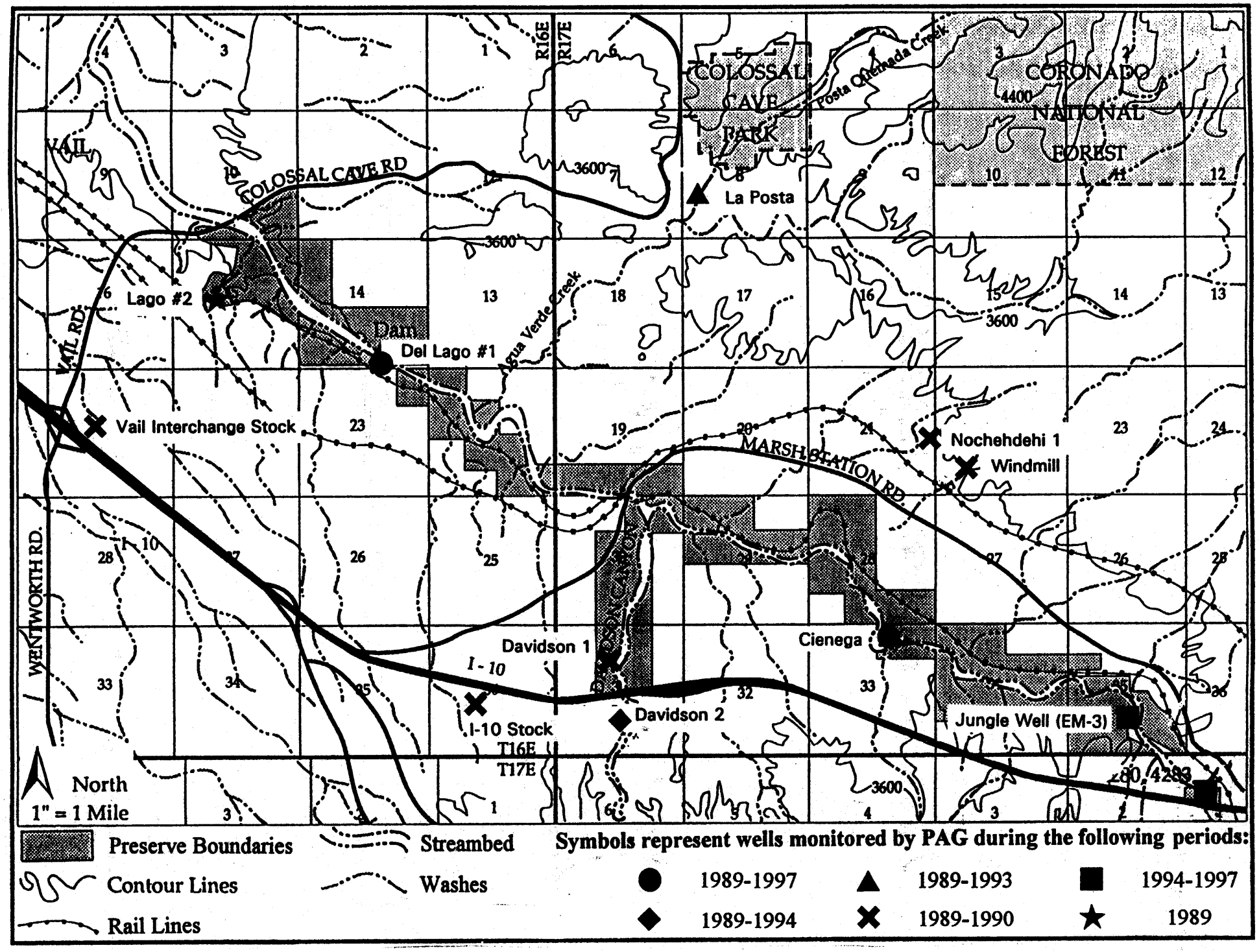



**Figure 7: Locations of Wells included in PAG's Groundwater Level Monitoring Program**

* Note: Base map provided to PAG by Pima County Flood Control District

## Table 4. Construction and Location Information for Wells Included in Groundwater Monitoring Program

| Well Name | Well Location | Status* | Casing Diameter (Inches) | Well Depth (Feet) | Aquifer | Land Surface Elevation (Feet) | Measuring Point Height (Feet) | Measuring Point Elevation (Feet) |
|---|---|---|---|---|---|---|---|---|
| Del Lago #1 | D-16-16-14DDC | Unused-Municipal | 16 | 308 | Earp Fm. | 3241 | 2.0 | 3243 |
| Cienega | D-16-17-33ABB | Capped - Stock | 12 | 80 | Alluvium*** | 3428 | 1.5 | 3430 |
| Jungle Well (EM-3) | D-16-17-35DBC3 | Unequipped Monitor | 6 | 115 | Alluvium*** | 3552 | 2.6 | 3555 |
| Empirita #1 | D-17-17-1BCA | Capped | 8 | 87 | Alluvium*** | 3555 | 0.0 | 3555 |
| Empirita #2 (EE-1) | D-17-17-1DDD2 | Exploration | 16,12,8 | 565 | Pantano Fm. | 3615 | 1.8 | 3617 |
| Windmill | D-16-17-22CBD | Active Stock | N/A | N/A | N/A | 3535 | 0.7 | 3536 |
| La Posta | D-16-17-8CBD | Inactive - Stock | 72 | N/A | N/A | 3408 | 0.8 | 3409 |
| I-10 Stock | D-16-16-36CAB | Inactive - Stock | 12 | N/A | N/A | 3527 | 1.5 | 3529 |
| Davidson 1 | D-16-17-31BDD | Inactive - Stock | 12 | 150 | N/A | 3400 | 2.1 | 3402 |
| Davidson 2 | D-16-17-31DCA | Inactive - Stock | 16 | N/A | N/A | 3457 | 1.0 | 3458 |
| Nochehdehi 1** | D-16-17-20DAA | Unused -Domestic | 6 | 500 | N/A | 3465 | 2.33 | 3467 |
| Lago #2 | D-16-16-15CBB | Active Municipal | 16 | 604 | N/A | 3265 | 2.2 | 3267 |
| Vail Interchange Stock | D-16-16-21BDC | Inactive - Stock | 6 | 629 | N/A | 3262 | 0.67 | 3264 |

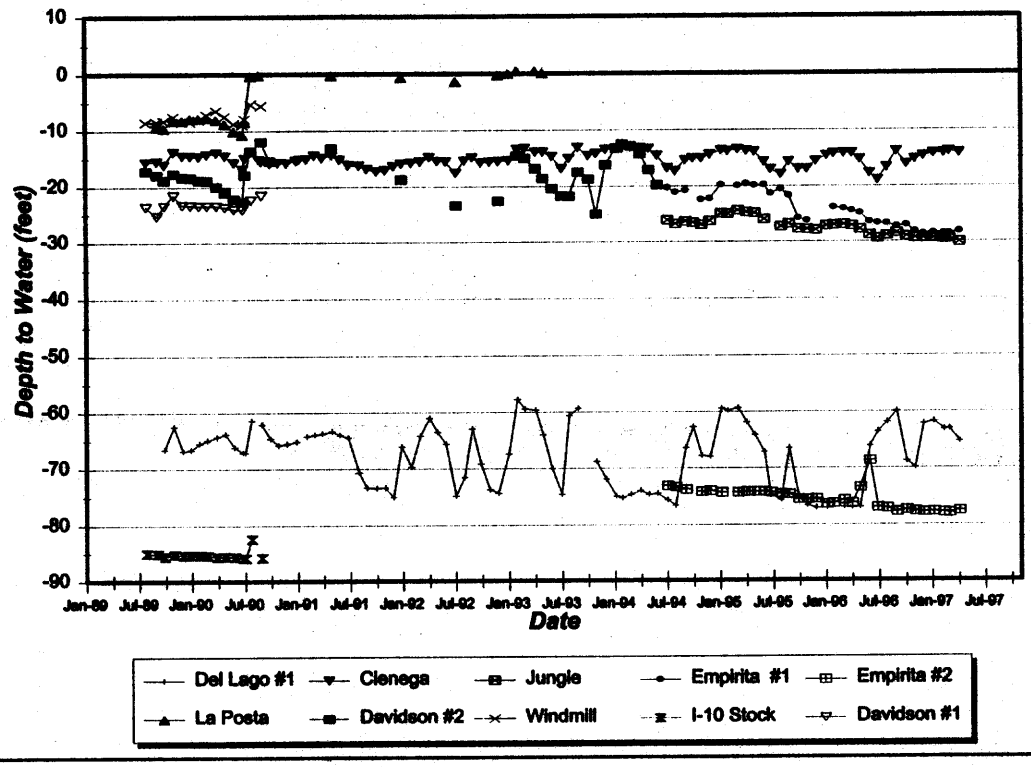
* status during monitoring period
** re-drilled to 800 feet and equipped 12/30/89
*** younger alluvium and/or basin fill alluvium
N/A = not available

### Monitoring Results and Water Level Trends

Table 5 lists the monitoring periods and number of water level measurements for each of the 13 wells included in PAG's monitoring program, as well as the maximum, minimum, and average water level depths measured. All water level depths are reported as feet below land surface. Average water levels varied from less than 10 feet below land surface at some wells to more than 500 feet below land surface at other wells. Most of the measurements were made at wells where the water level was less than 100 feet below land surface. Appendix C includes a tabulation of all the monthly water level data that PAG has collected since 1989. Depths to water and water table elevations are shown on Figures 8 and 9 for all wells that were measured at least 10 times.

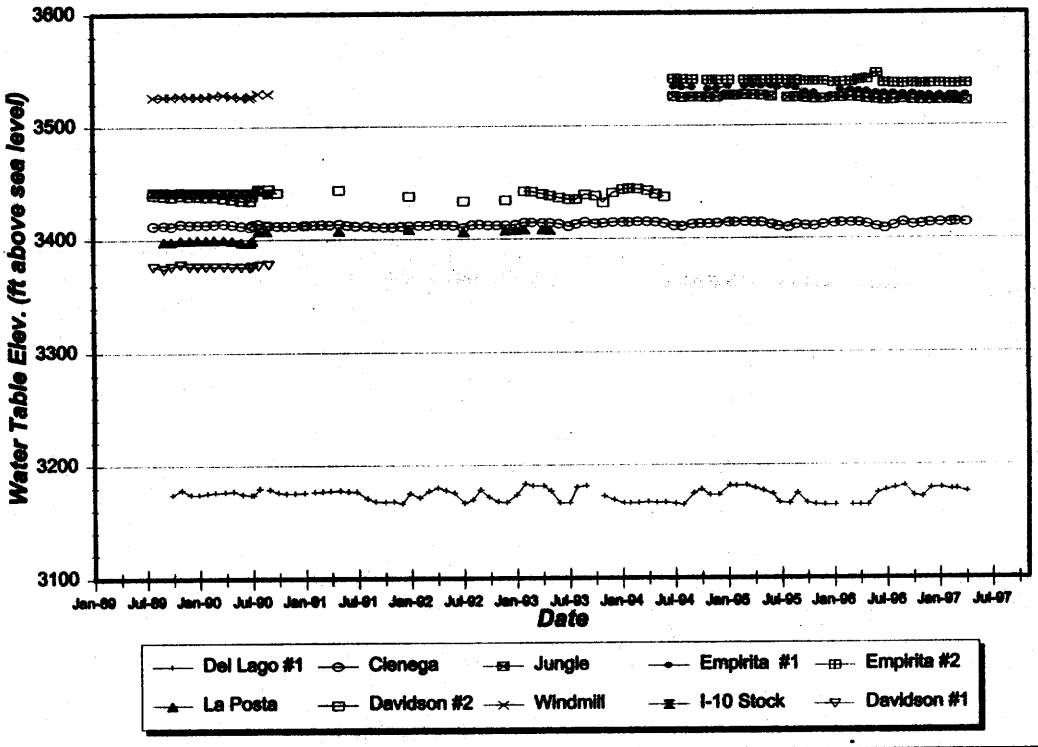
## Figure 8: Cienega Creek Groundwater Levels

Depths to Water at Selected Wells




## Figure 9: Cienega Creek Water Table Elevations

Water Table Elevations at Selected Wells



## Table 5. Summary of Groundwater Monitoring Results

| Well Name | Well Location | Monitoring Period | Number of Measurements | Maximum WL Depth (Feet) | Minimum WL Depth (Feet) | Average WL Depth (Feet) |
|---|---|---|---|---|---|---|
| **Del Lago #1** | D-16-16-14DDC | 1989 - 1997 | 92 | 77.02 | 57.70 | 67.52 |
| **Cienega** | D-16-17-33ABB | 1989 - 1997 | 96 | 18.95 | 13.06 | 15.09 |
| **Jungle Well (EM-3)** | D-16-17-35DBC3 | 1994 - 1997 | 33 | 30.07 | 24.23 | 27.31 |
| **Empirita #1** | D-17-17-1BCA | 1994 - 1997 | 30 | 28.63 | 19.53 | 24.07 |
| **Empirita #2 (EE-1)** | D-17-17-1DDD2 | 1994 - 1997 | 32 | 77.89 | 68.58 | 75.27 |
| **Windmill** | D-16-17-22CBD | 1989 - 1990 | 15 | 8.91 | 5.20 | 7.61 |
| **La Posta** | D-16-17-8CBD | 1989 - 1993 | 22 | 10.62 | -0.50 | 4.78 |
| **I-10 Stock** | D-16-16-36CAB | 1989 - 1990* | 15 | 85.75 | 82.37 | 85.18 |
| **Davidson 1** | D-16-17-31BDD | 1989 - 1990 | 15 | 25.15 | 21.42 | 23.22 |
| **Davidson 2** | D-16-17-31DCA | 1989 - 1994 | 37 | 24.91 | 11.96 | 17.93 |
| **Nochehdehi 1** | D-16-17-20DAA | 1989 - 1990** | 6 | 236.39 | 187.04 | 205.10 |
| **Lago #2** | D-16-16-15CBB | 1989 - 1989 | 1 | 334.30 | 334.30 | 334.30 |
| **Vail Interchange Stock** | D-16-16-21BDC | 1989 - 1990 | 4 | 529.33 | 528.92 | 529.15 |

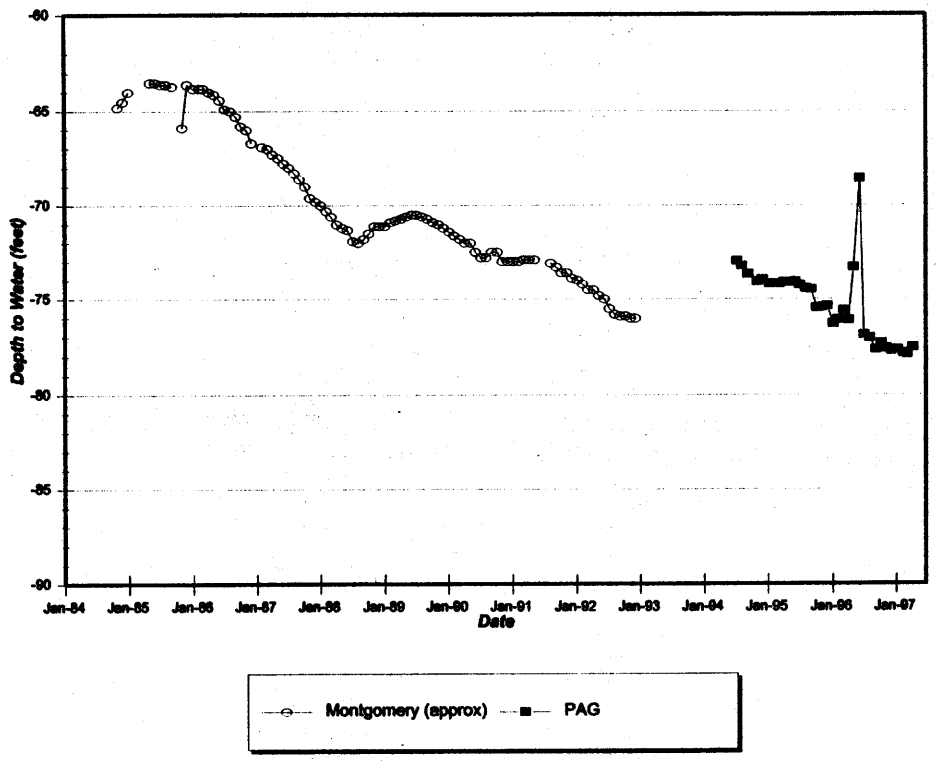
* measured dry on 12/2/92
**equipped 12/30/89; no access for 2/1/90 measurement

Between 1984 and 1997, an overall groundwater level decline of roughly 15 feet was observed in the upper reaches of the preserve, based on Montgomery and PAG data for the Empirita #2 and Jungle wells (Figures 10 and 11). A decline of about four feet was also observed at the Del Lago #1 well at the downstream end of the preserve between 1989 and 1997 (Figure 12). The sharpest decline at Jungle and Empirita #2 occurred between 1985 and 1988, followed by slighter declines through 1992. Water levels at Jungle and Empirita #2 had rebounded somewhat by 1994, but began declining again shortly afterwards, and continued declining through April 1997. The long-term decline in water levels probably reflected a change from unusually wet conditions in the early 1980s to drier conditions in the 1990s. In contrast, the water level at the Cienega well, near the middle of the preserve, remained essentially constant, presumably due to a greater volume of subsurface storage (Figure 13).

Monthly and seasonal variations in water levels were observed at most of the wells (Figures 10 to 19). Water level rises were common during the winter and early spring months, and in August and September during the summer thunderstorm season. Water level declines were common in the late spring and early summer months, and also in October, after the summer thunderstorm season ended. At the Cienega well (Figure 13), significant water level peaks were recorded four times in March, four times in September, twice in April, and once each in November, August, and May. Significant water level minimums were recorded four times in July, four times in October, and twice in August. At the Del Lago #1 well (Figure 12), significant water level peaks were recorded four times in September, twice in January, twice in May, and once each in March, April, August, October, and November. Significant water level minimums were recorded four times in December, three times in July, three times in August, twice in November, and once in February.

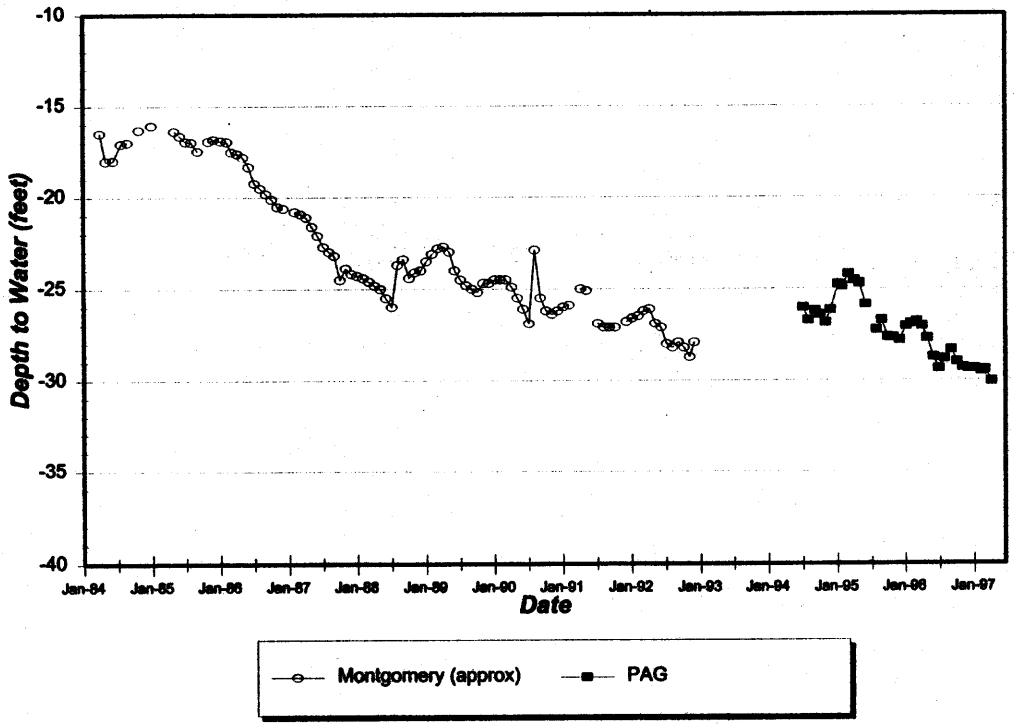
## Figure 10. Empirita #2 Well Groundwater Levels

January 1984 - April 1997



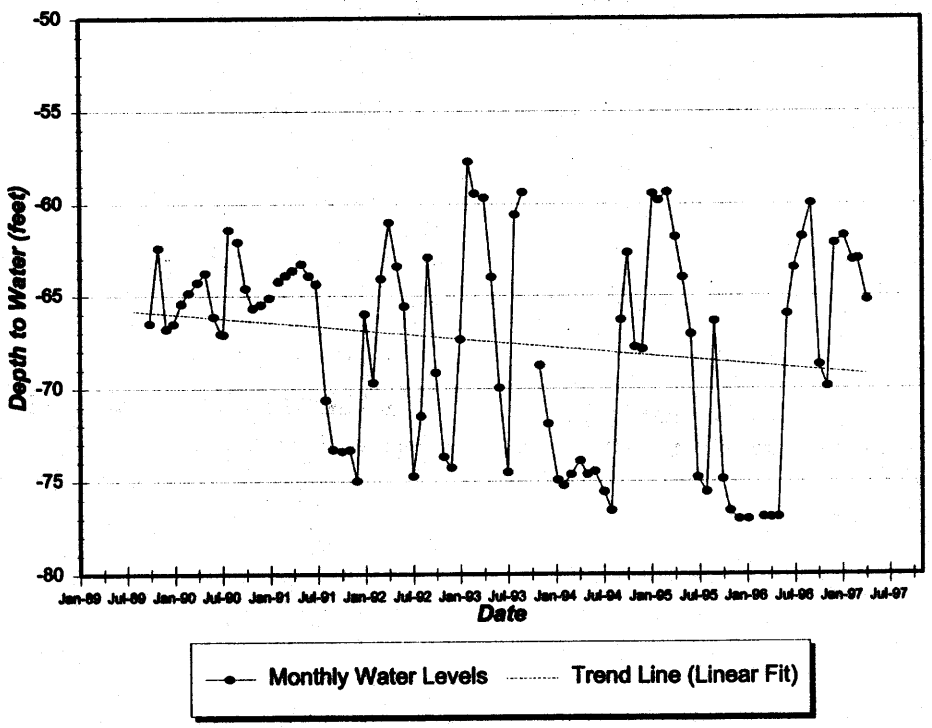

## Figure 11. Jungle Well Historical Groundwater Levels

January 1984 - April 1997



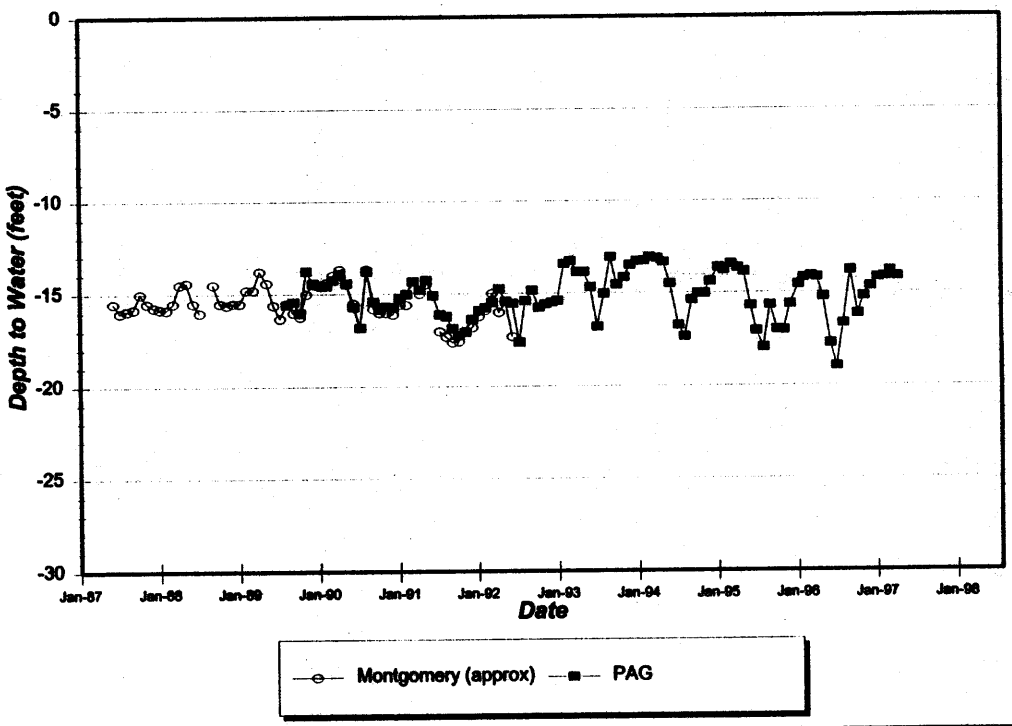
## Figure 12: Del Lago #1 Groundwater Levels

October 1989 - April 1997




## Figure 13. Cienega Well Historical Groundwater Levels

June 1987 - April 1997



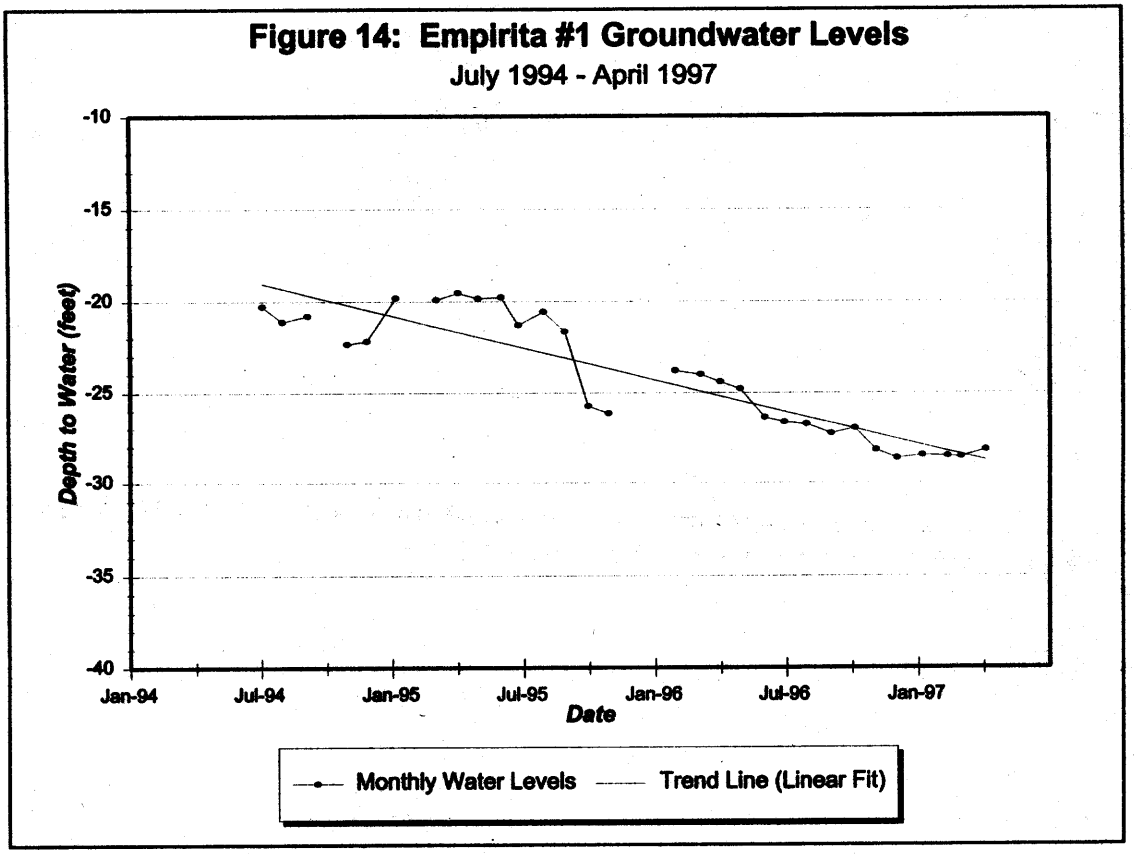


Figure 14: Empirita #1 Groundwater Levels
July 1994 - April 1997
-10
-15
-20
-25
-30
-35
-40
Depth to Water (feet)
Jan-94
Jul-94
Jan-95
Jul-95
Jan-96
Jul-96
Jan-97
Date
Monthly Water Levels
Trend Line (Linear Fit)

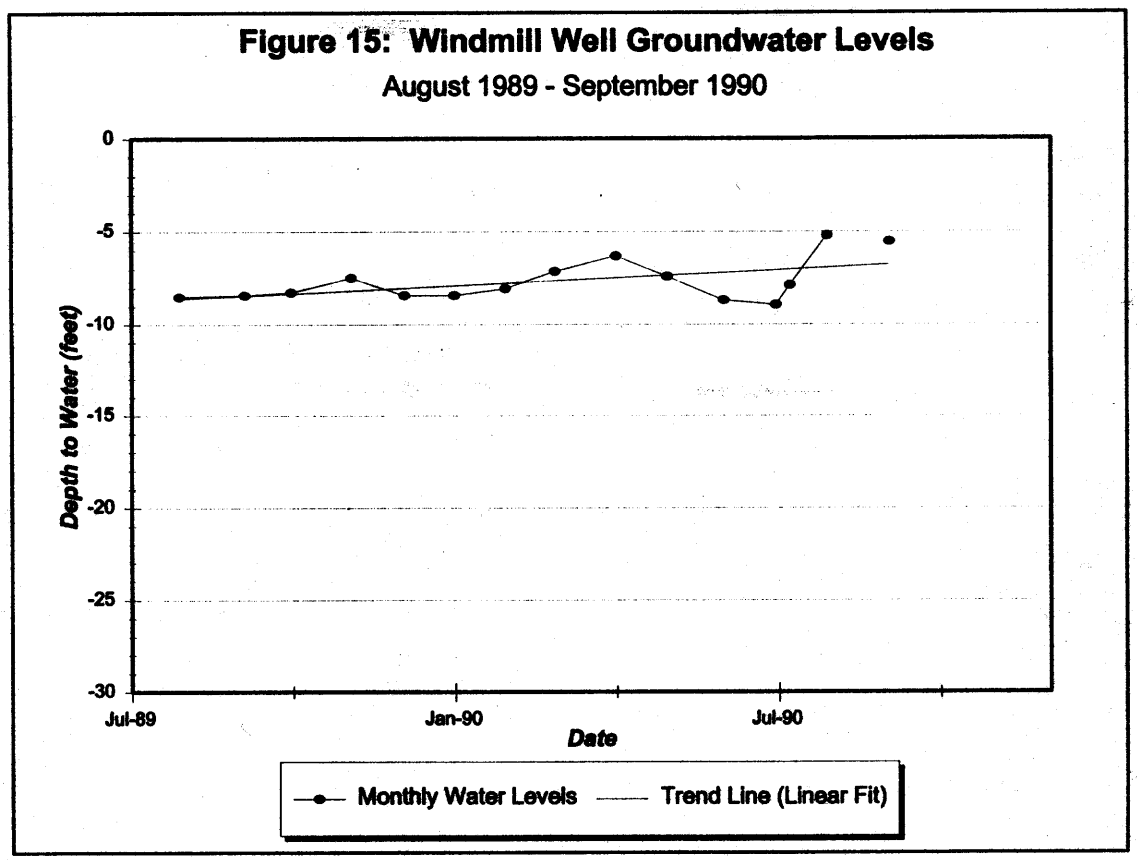


Figure 15: Windmill Well Groundwater Levels
August 1989 - September 1990
0
-5
-10
-15
-20
-25
-30
Depth to Water (feet)
Jul-89
Jan-90
Jul-90
Date
Monthly Water Levels
Trend Line (Linear Fit)

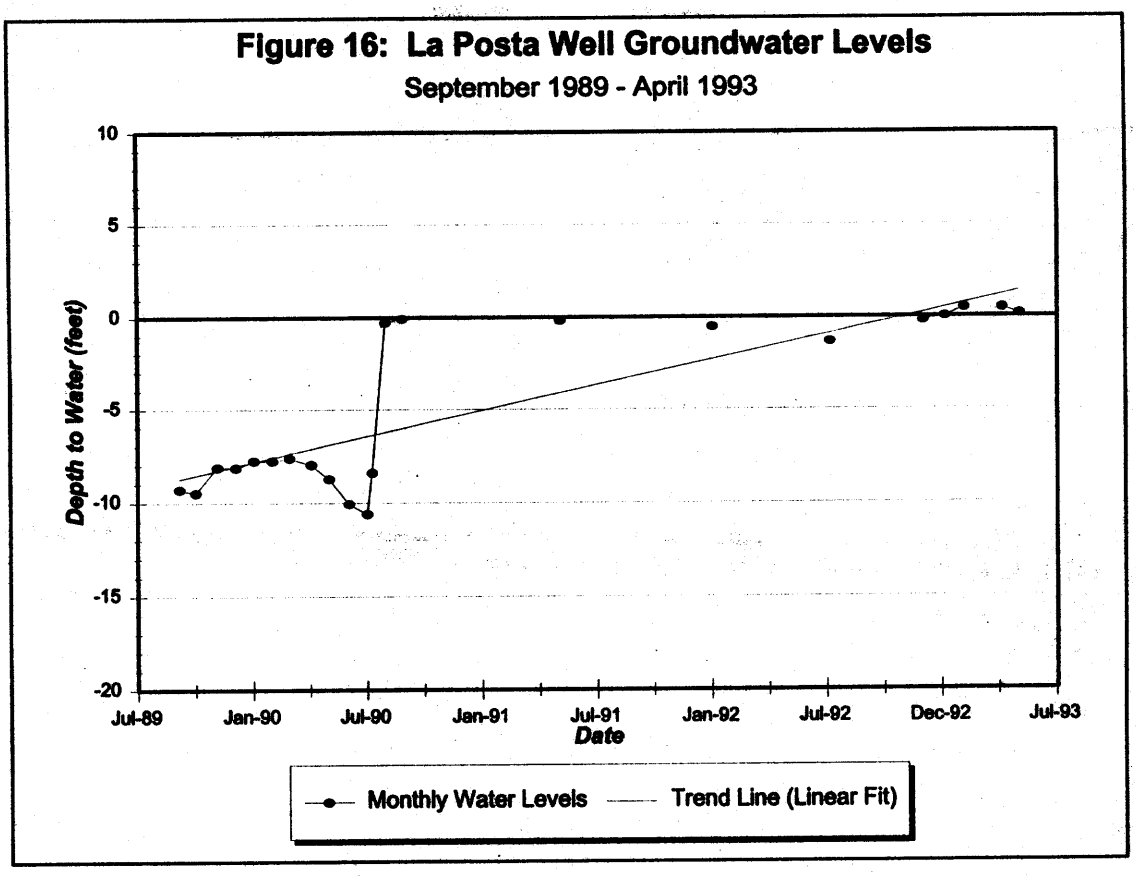


Figure 16: La Posta Well Groundwater Levels
September 1989 - April 1993
10
5
0
-5
-10
-15
-20
Depth to Water (feet)
Jul-89
Jan-90
Jul-90
Jan-91
Jul-91
Jan-92
Jul-92
Dec-92
Jul-93
Date
Monthly Water Levels
Trend Line (Linear Fit)

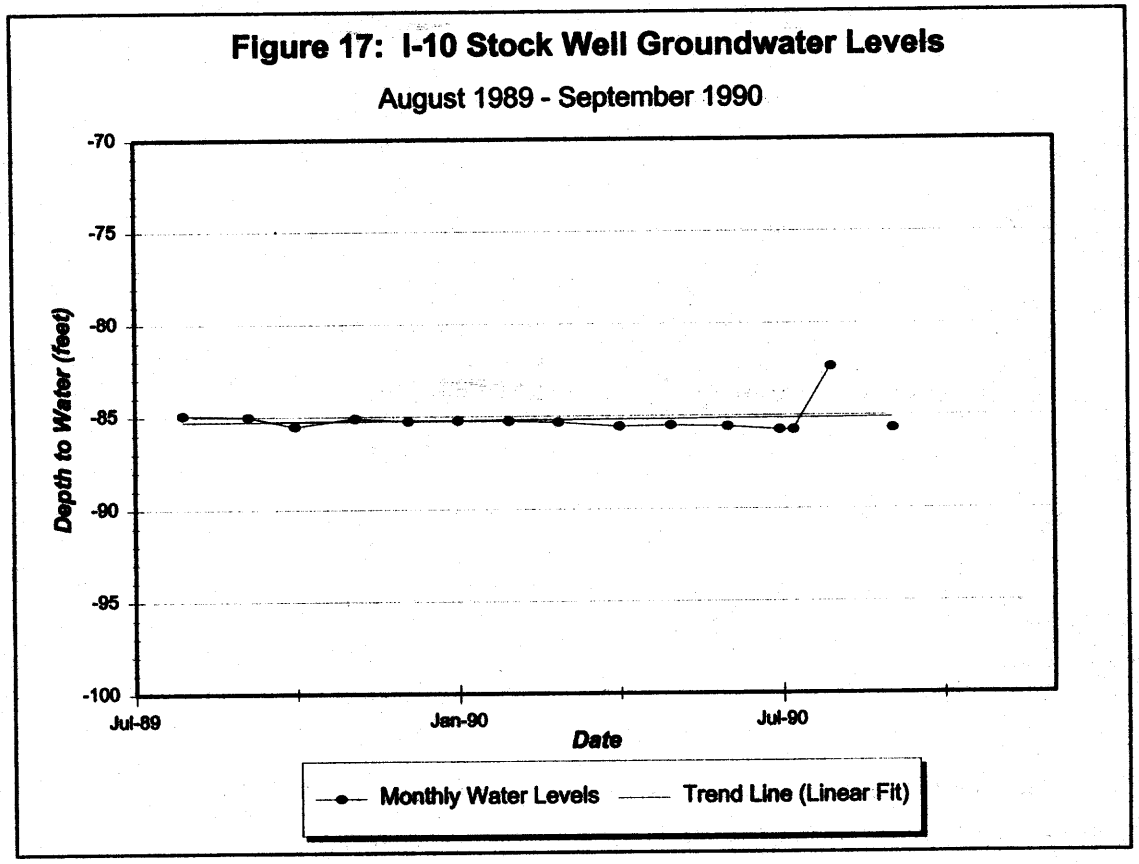


Figure 17: I-10 Stock Well Groundwater Levels
August 1989 - September 1990
-70
-75
-80
-85
-90
-95
-100
Depth to Water (feet)
Jul-89
Jan-90
Jul-90
Date
Monthly Water Levels
Trend Line (Linear Fit)

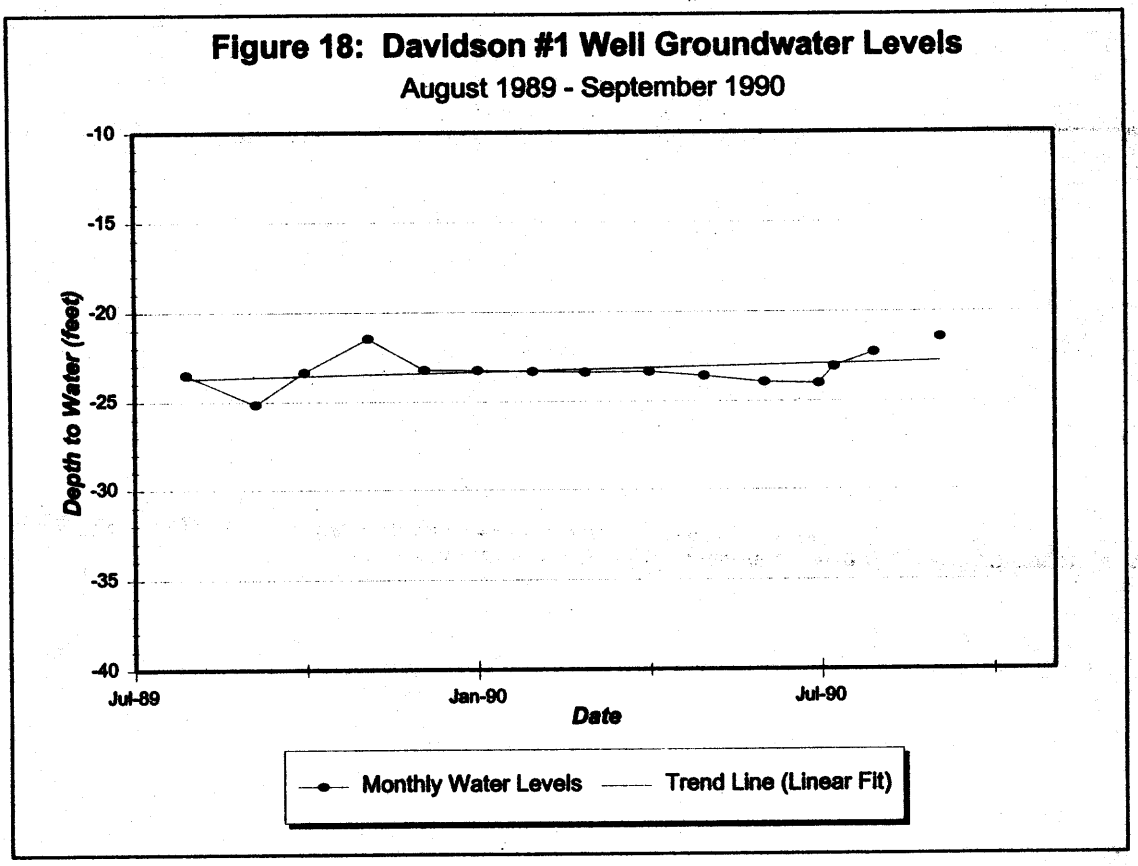


Figure 18: Davidson #1 Well Groundwater Levels
August 1989 - September 1990
-10
-15
-20
-25
-30
-35
-40
Depth to Water (feet)
Jul-89
Jan-90
Jul-90
Date
Monthly Water Levels
Trend Line (Linear Fit)

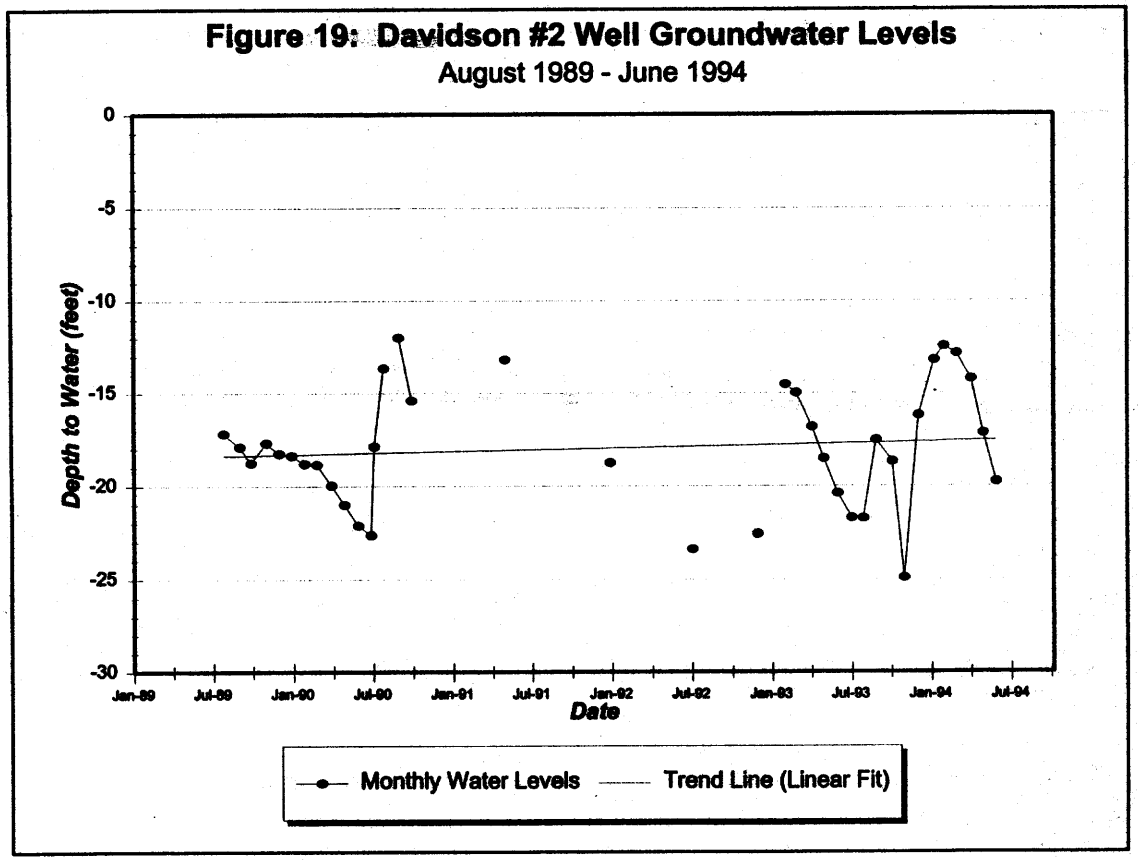


Figure 19: Davidson #2 Well Groundwater Levels
August 1989 - June 1994
0
-5
-10
-15
-20
-25
-30
Depth to Water (feet)
Jan-89
Jul-89
Jan-90
Jul-90
Jan-91
Jul-91
Jan-92
Jul-92
Jan-93
Jul-93
Jan-94
Jul-94
Date
Monthly Water Levels
Trend Line (Linear Fit)

Of all the wells that PAG has monitored, monthly and seasonal water level variations appeared to have the largest magnitude at the Del Lago #1 and Davidson #2 wells (more than 10 feet in a single season), and the smallest magnitude at the Cienega and Jungle wells (less than 5 feet in a single season). Water levels at the Del Lago #1 well became significantly more variable in 1992; prior to 1992, seasonal variations were on the order of 5 feet.

PAG recorded short-term water level variations at some wells that appeared to be inconsistent with data from other wells. For example, in the late summer of 1990, the La Posta well abruptly rose more than 10 feet, to a level near land surface (Figure 16). The well remained at the higher level and eventually began showing artesian conditions in early 1993. No other wells showed this trend. Another example is seen in the graph for the Empirita #2 well (Figure 10), which intercepts the Pantano formation. The water level at Empirita #2 rose about 7 feet from April to June of 1996, and then suddenly dropped about 8 feet between June and July of 1996. None of the other wells monitored at the time showed this sudden rise and drop, except possibly the Del Lago #1 well, which is the only other well in the current monitoring program that does not tap the younger alluvial aquifers. The water level at the Del Lago #1 well rose about 11 feet between May and June of 1996 and dropped about 10 feet between September and November of 1996 (Figure 12).

Water level trends were fairly consistent between the Del Lago #1 well (Figure 12) and the Cienega well (Figure 13), which were the only two wells PAG monitored during the entire period. Trends were especially consistent between July 1989 and July 1993. Several exceptions were noted after this period, however. In spring 1994, water levels rose for four consecutive months at the Cienega well and dropped during the same four months at the Del Lago #1 well. Water level trends were consistent between the wells from the summer of 1994 until the fall of 1995, but they were highly inconsistent from the fall of 1995 through the summer of 1996, during the drought that affected the region. From October 1995 through March 1996, water levels rose about three feet at the Cienega well and dropped about two feet at the Del Lago #1 well. Then, from March 1996 through July 1996, water levels at the Cienega well dropped about 5 feet while water levels at the Del Lago #1 well rose about 14 feet. Water levels recovered at the Cienega well by September 1996, and trends were fairly consistent afterwards. Throughout the monitoring period, the magnitude of water level variations at the Del Lago #1 well was significantly greater than the magnitude of water level variations at the Cienega well. This suggests a greater volume of shallow subsurface storage at the Cienega well, and it likely reflects differences in lithologies at the two well sites. The Del Lago #1 well is probably drilled into limestone of the Paleozoic Earp Formation (Richard, 1997; Richard and Harris, 1996), whereas the Cienega well is drilled into younger alluvial deposits. The correlation coefficient for water level data at the Cienega and Del Lago wells was 0.35, which was fairly low, indicating that a linear relationship between water levels at the two wells did not exist. Influences of recharge along tributaries such as Agua Verde Creek and Davidson Canyon, which join Cienega Creek between the two wells, might contribute to inconsistencies between the wells' water level trends.

Groundwater Flow Directions

Figures 20 and 21 are water table elevation maps for the Cienega Creek Natural Preserve area for January 1990 and August 1990. The maps are based on data from

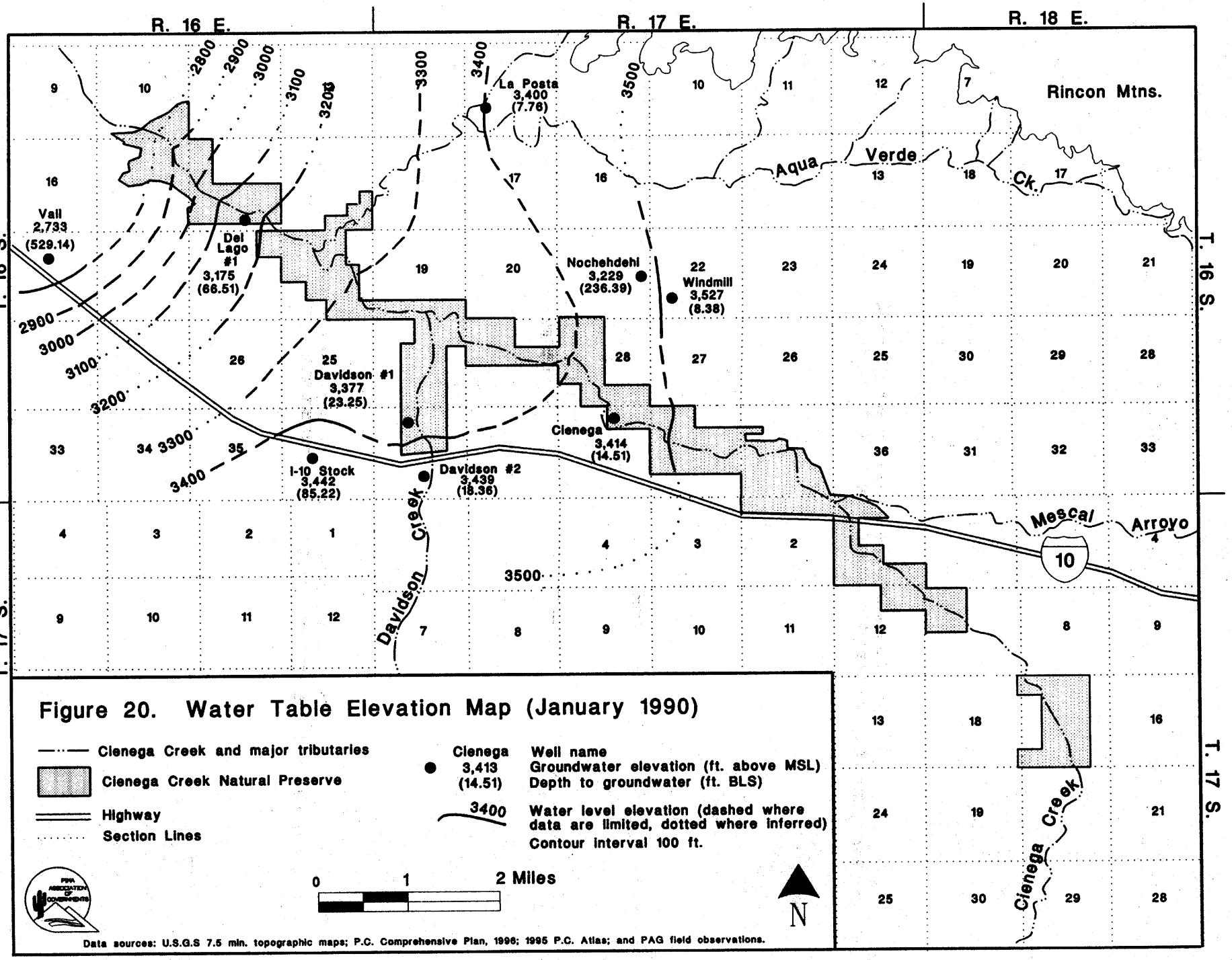
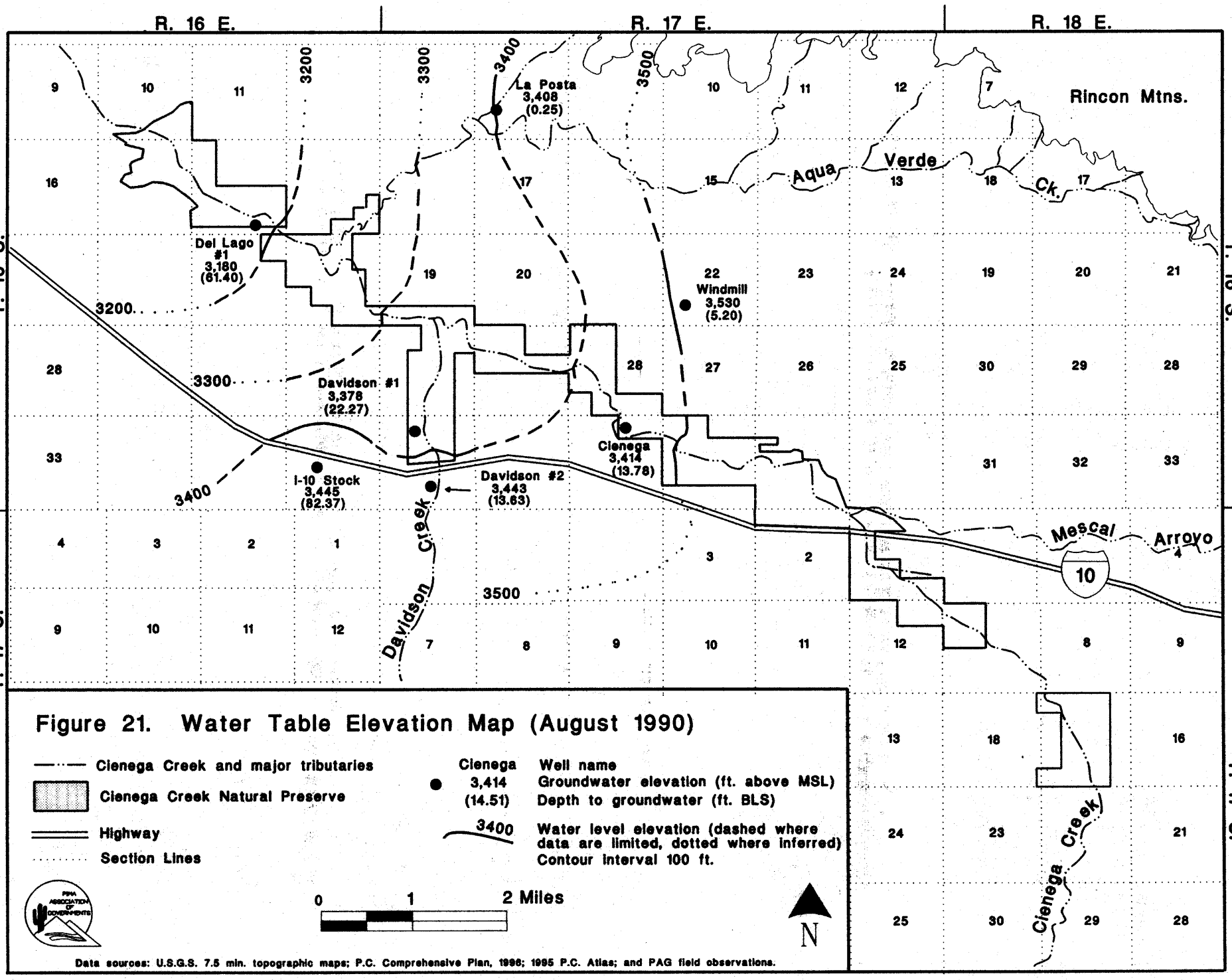



Figure 20. Water Table Elevation Map (January 1990)




## Figure 21. Water Table Elevation Map (August 1990)

- Cienega Creek and major tributaries
- Cienega Creek Natural Preserve
- Highway
- Section Lines

Cienega — Well name
3,414 — Groundwater elevation (ft. above MSL)
(14.51) — Depth to groundwater (ft. BLS)

3400 — Water level elevation (dashed where data are limited, dotted where inferred) Contour interval 100 ft.

0 1 2 Miles

N

Data sources: U.S.G.S. 7.5 min. topographic maps; P.C. Comprehensive Plan, 1996; 1995 P.C. Atlas; and PAG field observations.

PAG's groundwater monitoring program. Data from 1990, instead of 1997, were used because more wells were monitored in 1990. Based on Figures 20 and 21, the groundwater flow direction was generally from the mountains toward the creek, and along the creek to the northwest.

Comparison of Groundwater Trends to Precipitation

Precipitation trends were compared to groundwater levels in the lower Cienega basin. Analysis of regional precipitation trends (Section III) showed a very strong correlation between precipitation at various gages throughout Cienega basin. For simplicity, rainfall at Pima County Alert System (PCAS) gage 4280, located where Cienega Creek crosses Interstate 10, was chosen to represent precipitation in Cienega basin.

Figures 22 through 25 show trends in groundwater levels and precipitation versus time. Figures 22 and 23 show groundwater elevations at Cienega and Del Lago #1 wells versus precipitation at PCAS gage 4280. The graphs indicate that groundwater levels at these wells often responded to precipitation events within one month. In particular, Del Lago #1 well appeared to respond very strongly to precipitation events. Although the data were much more limited, similar trends were seen in the La Posta, Windmill, Davidson #1 & #2, and I-10 stock wells (Figures 24 and 25).

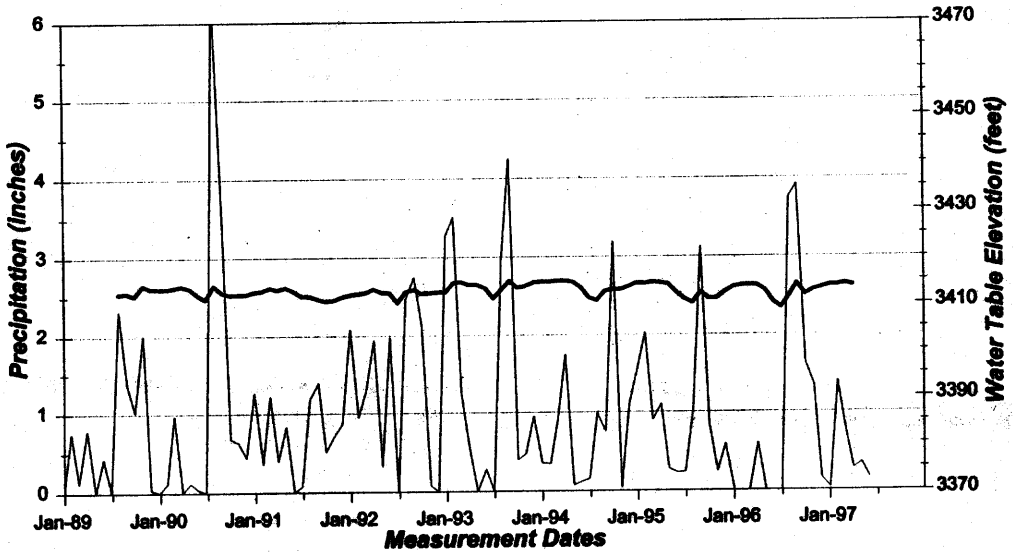
The magnitude of the water level rises did not necessarily reflect the magnitude of the increases in monthly precipitation totals. Also, some water level rises occurred without a corresponding increase in precipitation. Some of these water level rises might have occurred in response to a decrease in evapotranspiration during the winter months, or they might have reflected a delayed response to regional groundwater recharge. The cessation of pumping from large production wells would also explain these rises; however, PAG is not aware of any large production wells nearby.

Figure 25 illustrates trends in precipitation and groundwater levels at Jungle Well and Empirita #1 and #2 wells from July 1994 through April 1997. None of these wells showed a marked response to precipitation events during this period. The anomalous rise and fall in water levels at the Empirita #2 well during the spring and summer of 1996 did not appear to correlate with precipitation data from PCAS gage 4280. If the water level rise was a delayed response to the previous winter rains in either the upper or lower basin, then a similar response would be expected in 1994 and 1995. Instead, water levels in the Empirita #2 well did not show any significant fluctuations. The cause of this anomaly is not known.

Water level data for the Cienega and Del Lago #1 wells showed significant seasonal changes, but did not show any large long-term trends. In contrast, groundwater levels at the Jungle and Empirita wells showed minimal seasonal changes, but appeared to decline by as much as five to ten feet between 1994 and 1997. Decreased rainfall throughout the Cienega basin may have been responsible for the long term groundwater level declines. The lower Cienega basin and surrounding areas received, on average, 1 to 3 inches less rainfall per year in 1994, 1995, and 1996 than the same area received annually between 1989 and 1993. The upper basin received an average of 7.3 inches less rainfall and the Santa Rita Mountains received an average of 6.6 inches less rainfall annually in 1994, 1995, and 1996 than prior to that time (Appendix A). Increased pumpage might also explain the declines. However, no

## Figure 22: Precipitation & Groundwater Elevation vs. Time

Gage 4280 (PCAS) & Cienega Well

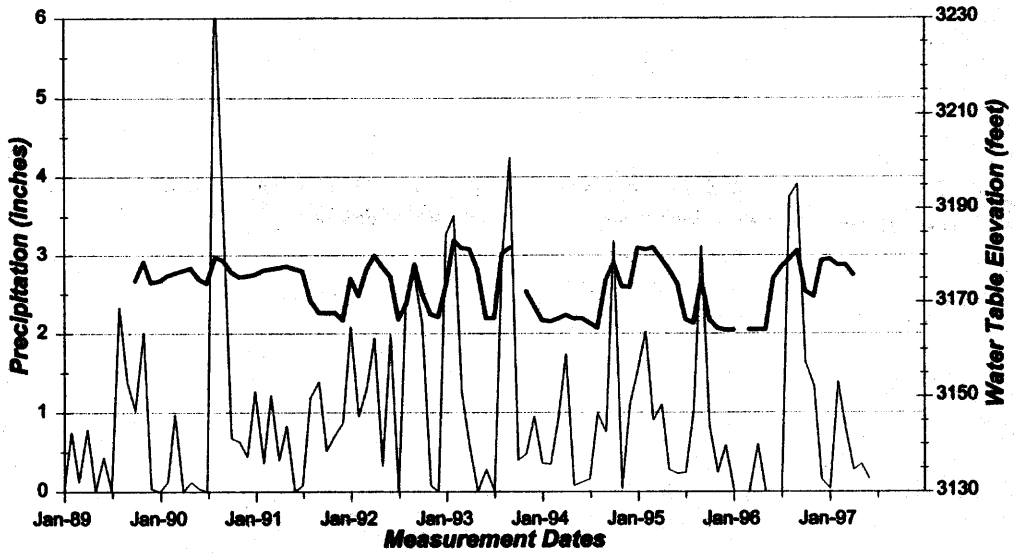



Precipitation: Gage 4280 (PCAS) — Groundwater Elevation: Cienega well

Data from Pima County Alert System database and PAG field measurements.

## Figure 23: Precipitation & Groundwater Elevation vs. Time

Gage 4280 (PCAS) & Del Lago #1 Well

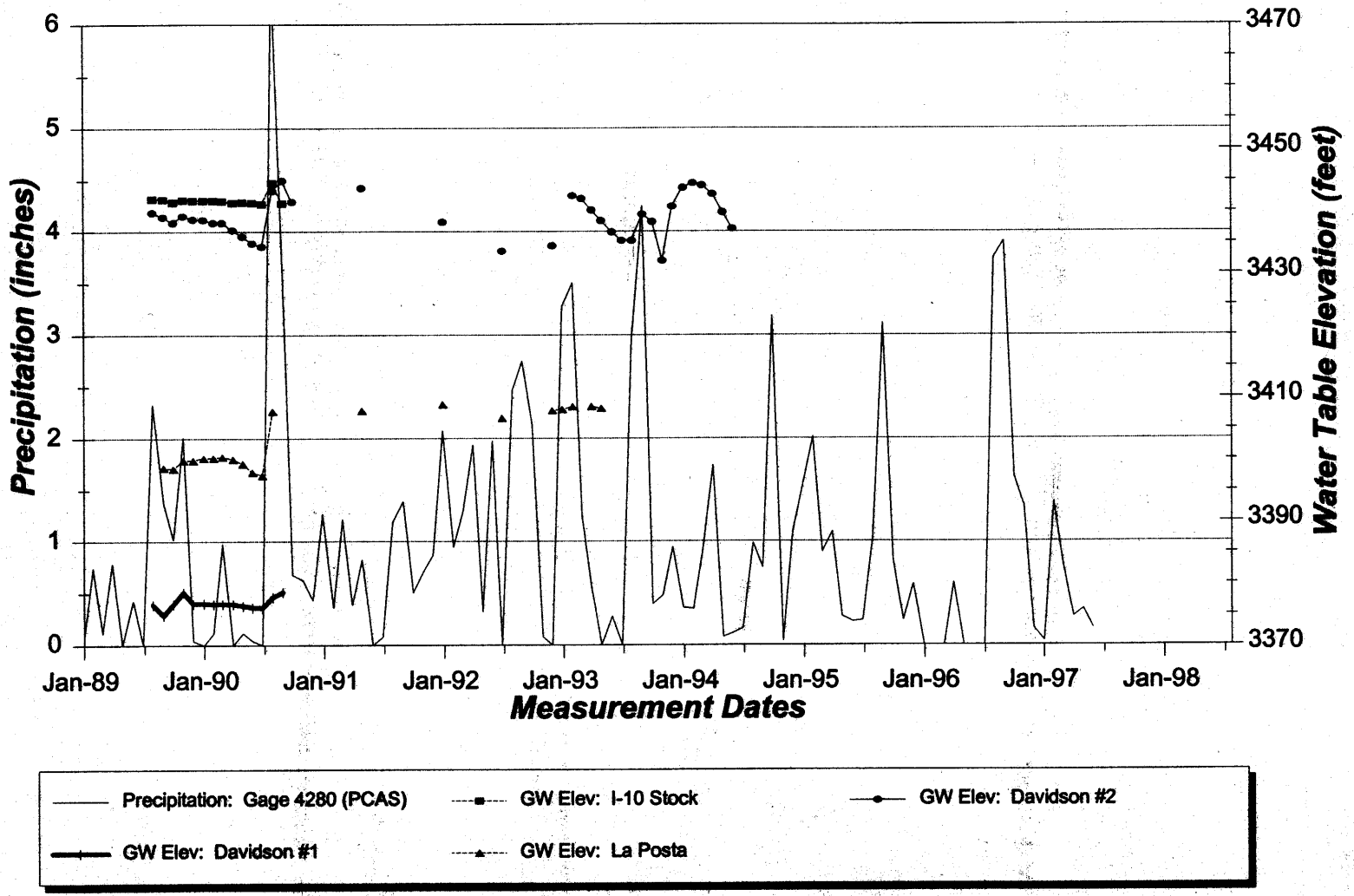



Precipitation: Gage 4280 (PCAS) — Groundwater Elevation: Del Lago #1

Data from Pima County Alert System database and PAG field measurements.

# Figure 24: Precipitation & Groundwater Elevations vs. Time

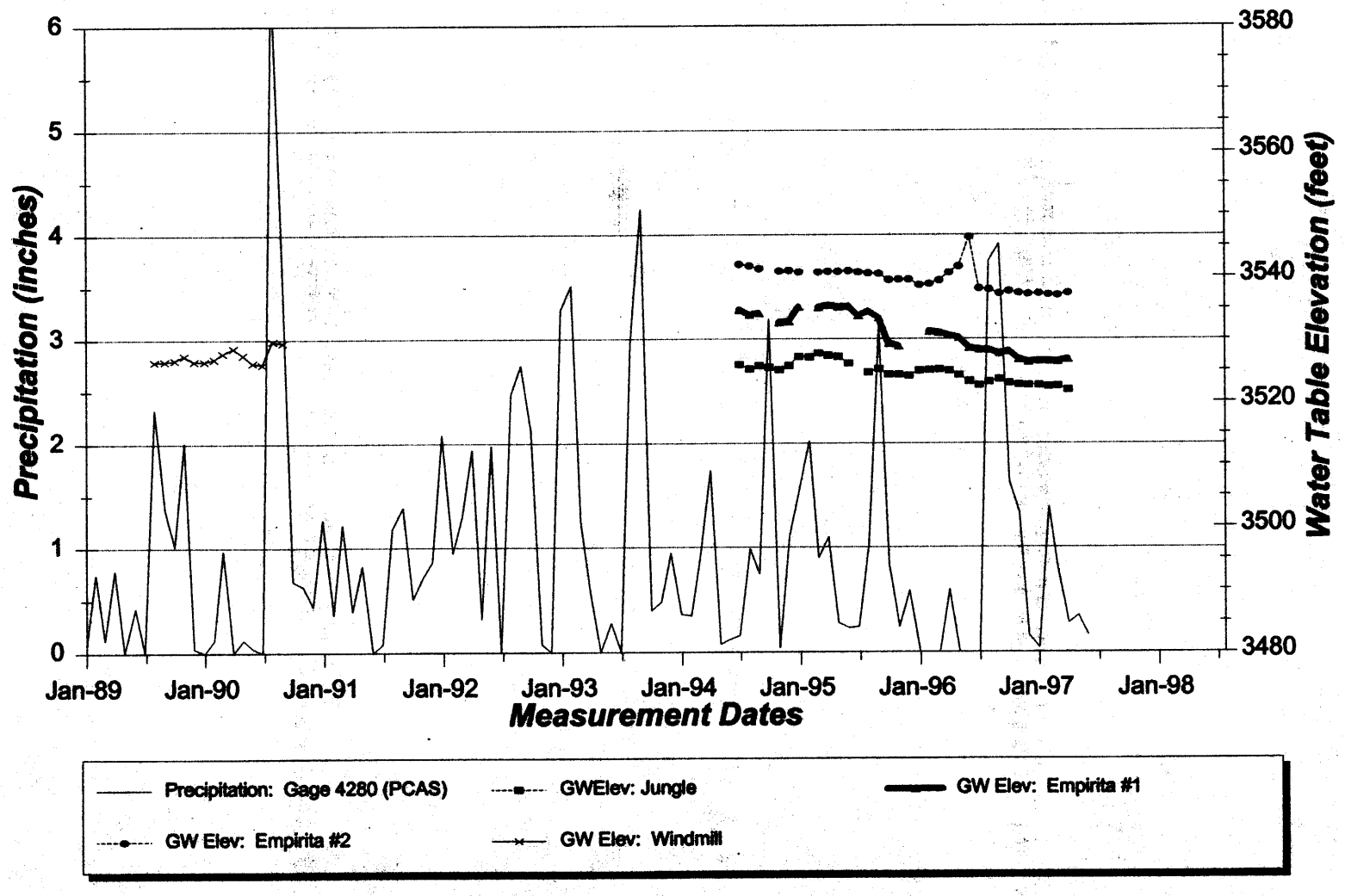
Gage 4280 (PCAS); La Posta, I-10 Stock, Davidson #1 & #2 Wells




Data from Pima County Alert System database and PAG field measurements.

# Figure 25: Precipitation & Groundwater Elevation vs. Time

## Gage 4280 (PCAS); Jungle, Windmill, Empirita #1 & #2 Wells




Data from Pima County Alert System database and PAG field measurements.

pumpage data for Empirita Ranch were available from ADWR.

In addition to evaluating temporal trends in precipitation and groundwater levels, PAG calculated correlation coefficients between monthly precipitation totals and groundwater elevations at the Del Lago #1 and Cienega wells. The correlation coefficients were calculated with the spreadsheet program QuattroPro. Values of 0.07 and -0.35 were calculated between precipitation at the Cienega/I-10 gage and the Del Lago #1 and Cienega wells, respectively, indicating no linear relationship between the precipitation recorded during a given month and the water level at these wells during the first week of the following month.

In summary, groundwater levels in the lower Cienega Creek basin often responded within one month to significant increases in monthly precipitation totals. The magnitude of the response was not necessarily proportional to the magnitude of the increase in precipitation. Water levels also dropped on many occasions within a month after a significant decrease in precipitation. On other occasions, however, particularly during the winter, water levels remained stable, or even rose, following a period with low precipitation. A varied response to longer-term trends in precipitation was also observed. Wells near the upstream margin of the preserve showed a general water level decline in response to drier conditions from 1994 to 1997, whereas water levels in wells in the central and downstream portions of the preserve remained essentially stable. Factors such as the intensity, duration, and regional distribution of individual precipitation events, regional variations in infiltration rates, transmissivities, and groundwater flow paths, and evapotranspiration were probably responsible for the variability of groundwater response to short- and long-term precipitation trends in the basin.

# V. SURFACE WATER MONITORING

PAG's Lower Cienega Creek surface water monitoring program began in 1989. The monitoring program was divided into two separate efforts. The first consisted of monitoring the extent of streamflow along various reaches. This effort, which was modified several times, began in 1989. The streamflow-extent monitoring was an important part of the monitoring program, because Cienega Creek is an interrupted stream, with perennial reaches separated by ephemeral and intermittent reaches. By documenting the locations that sustain surface flow, the effects of future groundwater withdrawals on the lengths of perennial and intermittent reaches can be evaluated. The second part of the monitoring program consisted of measuring stream discharge; this began in 1993. By firmly establishing baseline flow rates at selected locations along Cienega Creek, the effects of future groundwater withdrawals on Cienega Creek discharge can be evaluated. The following discussion includes data for both parts of the monitoring program through April 1997.

## Extent of Streamflow

PAG began monitoring the extent of streamflow at specific locations in the lower Cienega Creek watershed in 1989. The monitoring was usually conducted during the first week of each month. Monitoring during flood events was avoided, so that base flow conditions were recorded.

From 1989 to 1994, the streamflow-extent monitoring program consisted primarily of noting whether surface flow was present at various locations. After 1994, fewer locations were monitored, but the work at each site was expanded. Because of the significant changes that were made to the program in 1994, the discussion below is divided into two time periods: 1989 to 1994, and 1994 to 1997.

### 1989 to 1994

Between August 1989 and June 1994, PAG conducted observations of streamflow in and around the Cienega Creek Natural Preserve. Eighteen sites were included in the monitoring program. Their locations are shown on Figure 26. PAG's observations, which were made during the first week of each month, consisted of noting whether surface flow was present at each location. The observations at each site are summarized on Table 6.

As shown on Table 6, PAG's monitoring established whether flow was consistently present at certain locations. Flow was always, or nearly always, present in Cienega Creek at Del Lago Dam, Southern Pacific Milepost #1006, the Marsh Station Road crossing, the Cienega Well site, and the Tilted Bed site. In addition, Tilted Bed spring was nearly always flowing. In contrast, flow was rarely, or never, observed at: the Windmill site; the Mescal Wash site; in Davidson Canyon at the Cienega confluence or the Davidson #1 site; or in Cienega Creek at the Jungle Road crossing, the Colossal Cave Road crossing, or the I-10 crossing.

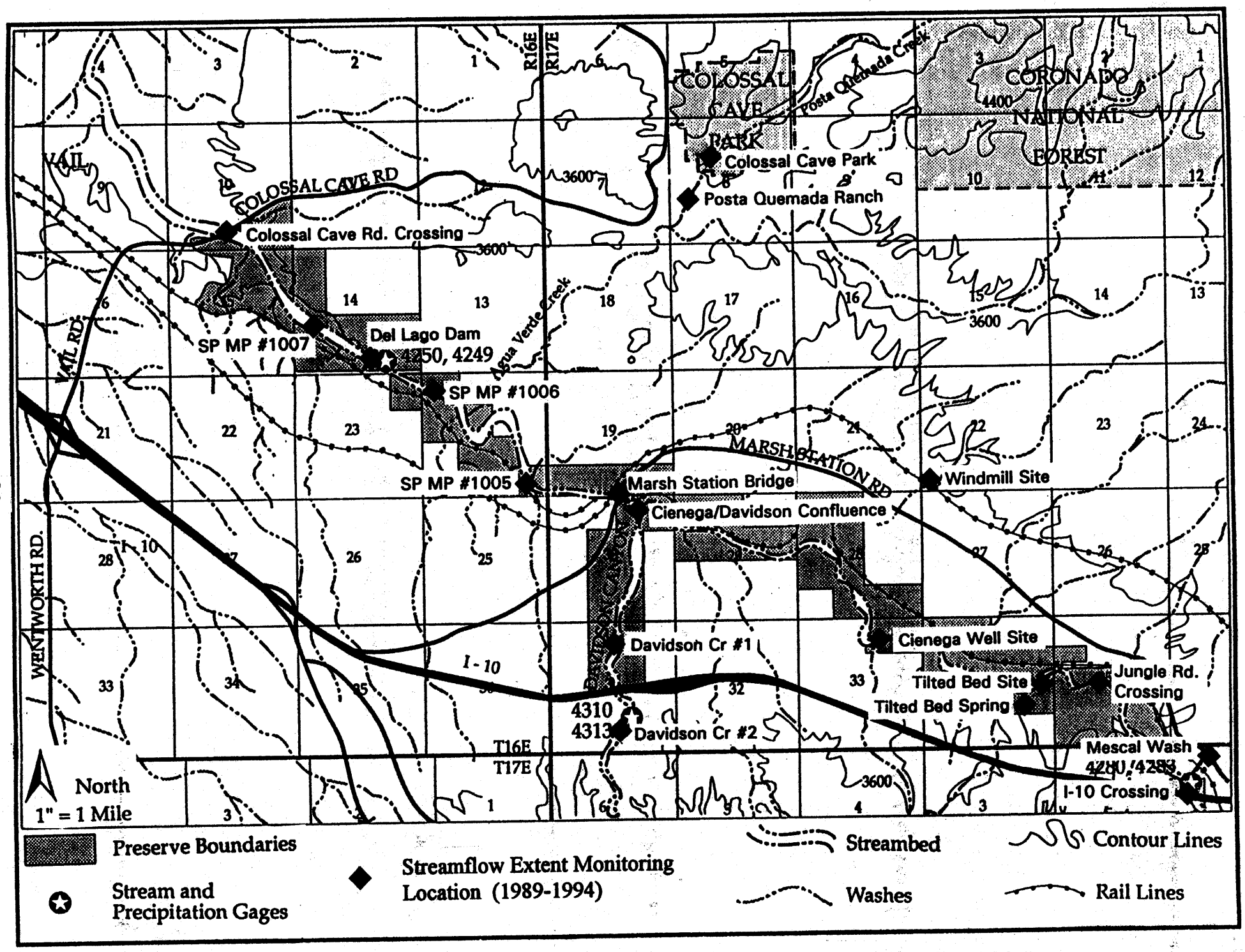



**Figure 26: Streamflow Extent Monitoring Locations (1989-1994)**

* Note: Base map provided to PAG by Pima County Flood Control District

**Table 6. Summary of Streamflow Observations from 1989 to 1994.**

| SITE | NUMBER OF OBSERVATIONS (years) | NUMBER OF TIMES FLOW OBSERVED | % OF TIME FLOW OBSERVED |
|---|---|---|---|
| Colossal Cave Rd Crossing | 41 (1990-94) | 3 | 7.3% |
| Colossal Cave Park | 26 (1991-93) | 3 | 11.5% |
| Posta Quemada Ranch | 37 (1989-93) | 16 | 43.2% |
| SP MP #1005 | 17 (1993-94) | 5 | 29.4% |
| Del Lago Dam | 57 (1989-94) | 57 | 100% |
| SP MP #1006 | 13 (1993-94) | 13 | 100% |
| SP MP #1007 | 13 (1993-94) | 2 | 15.4% |
| Marsh Station Road crossing | 46 (1990-94) | 46 | 100% |
| Cienega/Davidson Confluence | 16 (1993-94) | 0 | 0% |
| Windmill site | 42 (1989-93) | 0 | 0% |
| Cienega Well site | 58 (1989-94) | 58 | 100% |
| Tilted Bed Spring | 17 (1993-94) | 16 | 94.1% |
| Tilted Bed site | 17 (1993-94) | 17 | 100% |
| Jungle Road crossing | 17 (1993-94) | 0 | 0% |
| Mescal Wash | 39 (1991-94) | 0 | 0% |
| I-10 crossing | 52 (1989-94) | 1 | 1.9% |
| Davidson Creek #1 | 15 (1989-90) | 0 | 0% |
| Davidson Creek #2 | 57 (1989-94) | 11 | 19.3% |

At other sites, the observations were more variable. The Posta Quemada Ranch, Southern Pacific Milepost #1005, and Davidson Creek #2 sites contained flow between 15% and 50% of the time. Flow was most common at these sites during the spring months and after the summer thunderstorm season.

1994 to 1997

Between July 1994 and April 1997, PAG monitored the extent of streamflow at three locations in the Cienega Creek Natural Preserve. The three areas included a reach of Cienega Creek downstream from the Jungle Road crossing (T16S, R17E, Section 35 CA); a reach of Davidson Canyon upstream from its confluence with Cienega Creek (T16S, R17E, Section 30 AB); and a reach of Cienega Creek near Southern Pacific Railroad Mile Post #1006, upstream from Del Lago Dam (T16S, R16E, Section 24 BB). The sites are shown on Figure 27. These three reaches were chosen as monitoring sites because flow conditions tended to be dynamic, with streamflow either beginning or ending near each site. Streamflow was continuous across these sites only during periods of above-normal precipitation.

Each month, PAG observed extent of streamflow at the three locations in the field and recorded the locations on aerial photographs. For each site, PAG attempted to make all of the observations at roughly the same time of day; the observations were usually made during the first week of each month. The monitoring sometimes had to be rescheduled to avoid flood flows. PAG only recorded the locations of surface waters that were flowing continuously. Stagnant ponds, puddles, saturated stream sediments, etc., were not considered to be

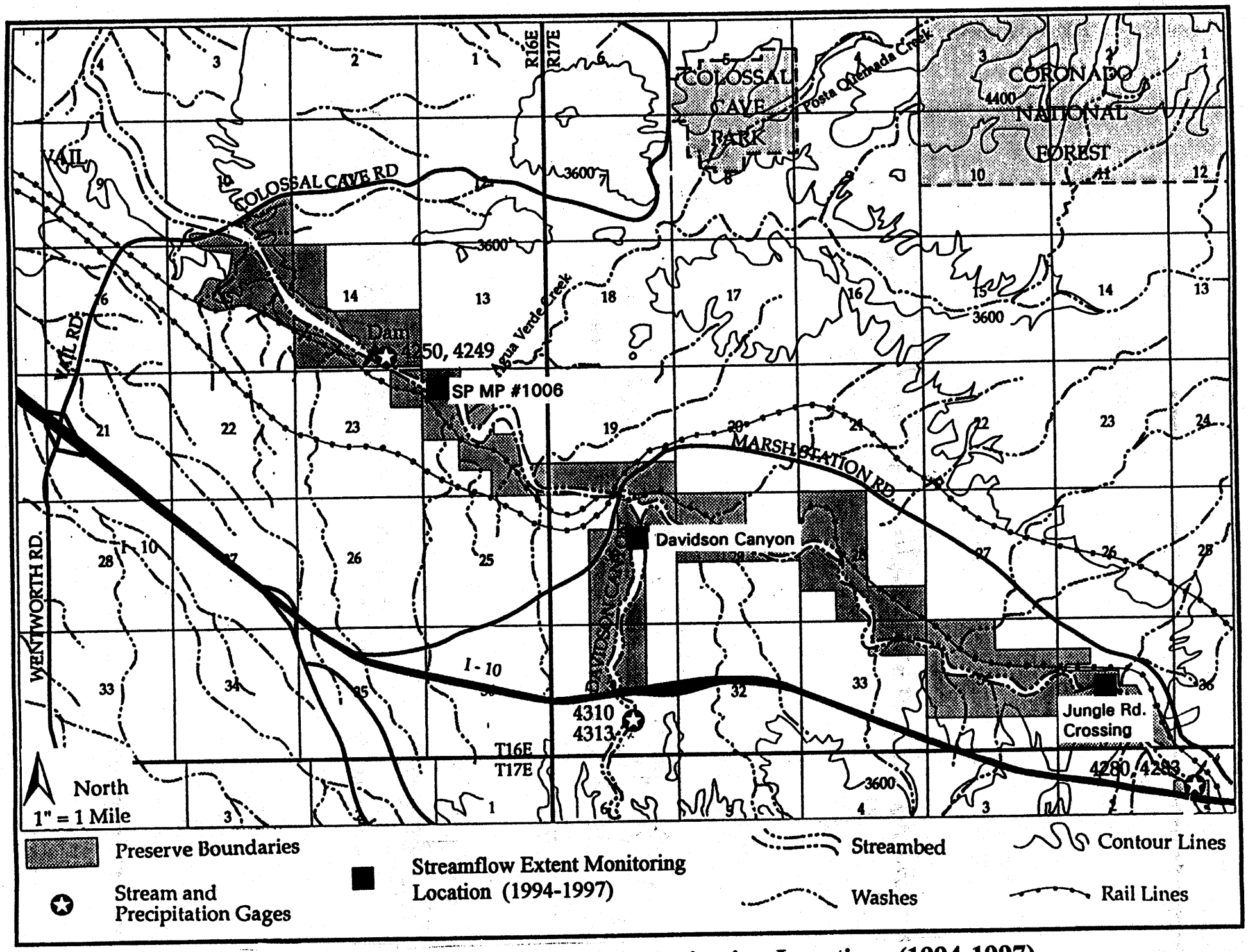



**Figure 27: Streamflow Extent Monitoring Locations (1994-1997)**

* Note: Base map provided to PAG by Pima County Flood Control District

streamflow.

The distances to the beginning or end of flow at the three sites were measured from discretionary reference points. All distances were measured along the center of the stream channel, rather than along a straight line. At the Jungle Road reach, the distance to the beginning of flow was measured downstream from where Cienega Creek intersects Jungle Road. The distance to the end of flow in Davidson Creek was measured upstream from the middle of the Davidson/Cienega Creek confluence. For the reach upstream from Del Lago Dam, the beginning-of-flow was measured upstream from a reference line extending north from Southern Pacific Railroad Mile Post #1006.

The results of PAG's monitoring are shown on Table 7, which lists the distances measured between the reference points and the beginning or end of flow at the three sites each month. During the three years of surface water monitoring, the extent of streamflow along the three reaches varied considerably.

At the Jungle Road site, seasonal and long-term trends were observed. The beginning-of-flow generally advanced upstream during the winter and spring months, and receded downstream during the summer and fall months. Annual variations in the location of the beginning-of-flow were also noted. For example, during January through May of 1995, the beginning-of-flow was between 360 feet and 400 feet downstream from the reference point, with continuous flow observed in March due to a storm event. During the same time period in 1996, streamflow began farther downstream, between 860 feet and an estimated 1870 feet from Jungle Road. From January through April 1997, the beginning of flow remained at a constant location, 1810 feet downstream from Jungle Road.

Over the course of the monitoring program, flow at the Jungle Road site often began near either of two locations. One location was between 350 and 750 feet downstream from Jungle Road, and the other was between 1750 and 1850 feet downstream from Jungle Road. These sites could be locations of subsurface bedrock highs which caused groundwater to discharge to the surface.

## Table 7. Streamflow Extent Monitoring Results

| Date | Distance downstream from Jungle Rd. to beginning of flow (Feet) | % of Reach with Flow | Distance downstream from end of flow in Davidson Canyon to confluence with Cienega Creek (Feet) | % of Reach with Flow | Distance upstream from SP #1006 to beginning of flow (Feet) | % of Reach with Flow |
|---|---|---|---|---|---|---|
| 7/8/94 | 630 | 68.5% | 950 | 13.6% | 185 | 18.5% |
| 8/5/94 | 630 | 68.5% | 1020 | 7.3% | 125 | 12.5% |
| 9/9/94 | 670 | 66.5% | No Flow | 0.0% | 595 | 59.5% |
| 10/5/94 | 720 | 64.0% | 920 | 16.4% | 430 | 43.0% |
| 11/3/94 | 710 | 64.5% | 930 | 15.5% | 320 | 32.0% |
| 12/1/94 | 700 | 65.0% | 930 | 15.5% | 430 | 43.0% |
| 1/10/95 | 380 | 81.0% | 480 | 56.4% | Continuous Flow | 100.0% |
| 2/1/95 | 360 | 82.0% | 460 | 58.2% | Continuous Flow | 100.0% |
| 3/7/95 | Continuous Flow | 100.0% | 410 | 62.7% | Continuous Flow | 100.0% |
| 4/6/95 | 380 | 81.0% | 480 | 56.4% | Continuous Flow | 100.0% |
| 5/4/95 | 400 | 80.0% | 460 | 58.2% | Continuous Flow | 100.0% |
| 6/5/95 | 740 | 63.0% | 950 | 13.6% | Continuous Flow | 100.0% |
| 6/29/95 | 950 | 52.5% | 980 | 10.9% | 850 | 85.0% |
| 8/3/95 | Flow off photo | 0.0% | No Flow | 0.0% | 440 | 44.0% |
| 9/1/95 | Flow off photo | 0.0% | No Flow | 0.0% | 880 | 88.0% |
| 10/4/95 | 1775 | 11.3% | No Flow | 0.0% | 550 | 55.0% |
| 11/1/95 | 1750 | 12.5% | No Flow | 0.0% | 420 | 42.0% |
| 12/4/95 | 1745 | 12.8% | No Flow | 0.0% | 250 | 25.0% |
| 1/9/96 | 1575 | 21.3% | No Flow | 0.0% | 245 | 24.5% |
| 2/1/96 | 860 | 57.0% | No Flow | 0.0% | 255 | 25.5% |
| 3/8/96 | 870 | 56.5% | No Flow | 0.0% | 425 | 42.5% |
| 4/4/96 | 1650 | 17.5% | No Flow | 0.0% | 445 | 44.5% |
| 5/2/96 | 1870 (est.) | 1.5% | No Flow | 0.0% | 445 | 44.5% |
| 6/5/96 | 2240 (est.) | 0.0% | No Flow | 0.0% | 300 | 30.0% |
| 7/2/96 | 2240 (est.) | 0.0% | No Flow | 0.0% | No Flow | 0.0% |
| 8/2/96 | 1850 | 7.5% | No Flow | 0.0% | 430 | 43.0% |
| 9/5/96 | 1850 | 7.5% | 950 | 13.6% | Continuous Flow | 100.0% |
| 10/8/96 | 2240 (est.) | 0.0% | 320 | 70.9% | 525 | 52.5% |
| 11/6/96 | 1850 | 7.5% | 160 | 85.5% | 525 | 52.5% |
| 12/5/96 | 1820 | 9.0% | 160 | 85.5% | 525 | 52.5% |
| 1/9/97 | 1810 | 9.5% | 160 | 85.5% | 530 | 53.0% |
| 2/13/97 | 1810 | 9.5% | 200 | 81.8% | Continuous except for 75 ft. reach | 95.0% |
| 3/4/97 | 1810 | 9.5% | 200 | 81.8% | Continuous | 100.0% |
| 4/7/97 | 1810 | 9.5% | 245 | 77.7% | 1040 | 100.0% |

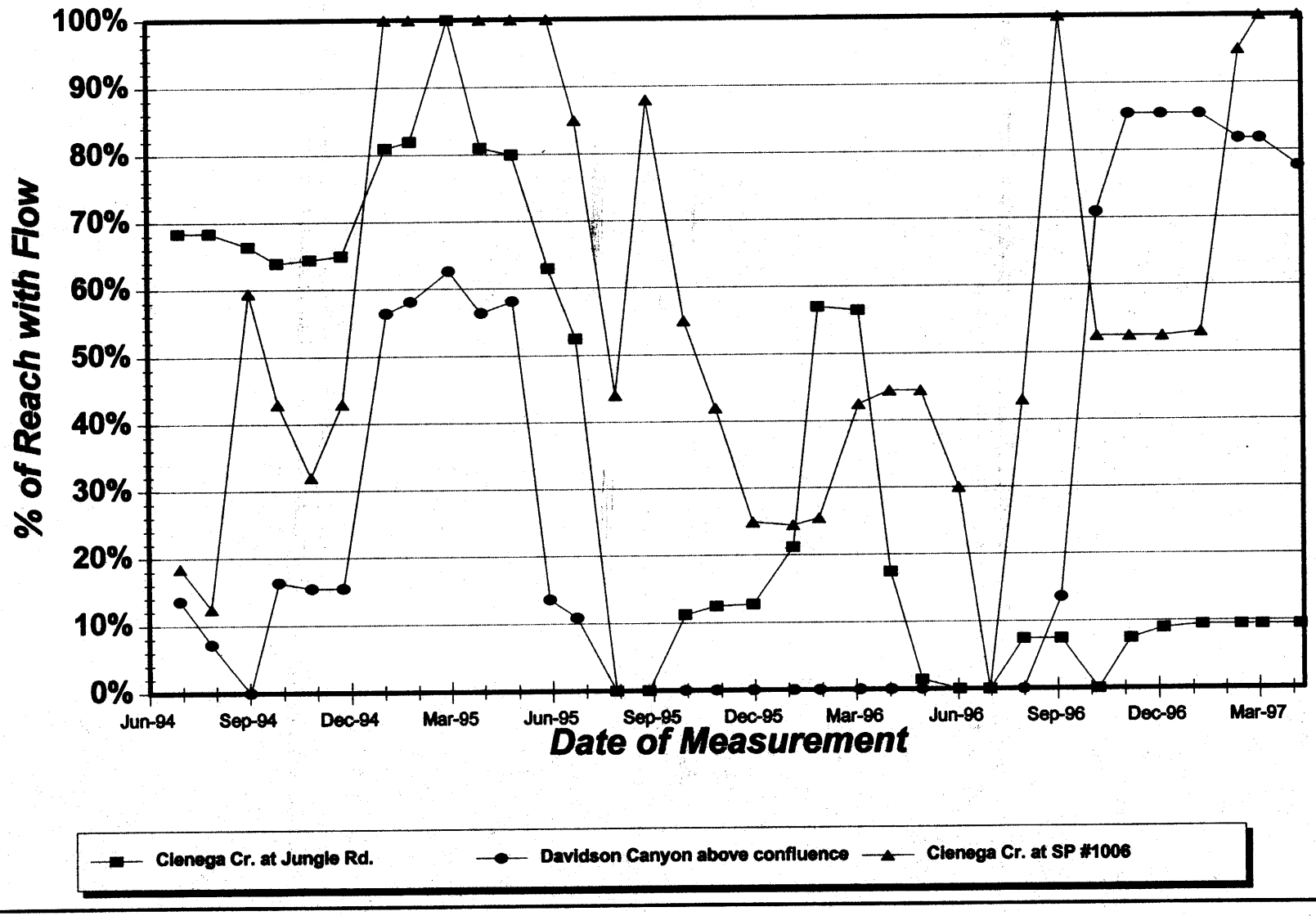
The Southern Pacific (SP) #1006 site showed seasonal trends similar to trends at the Jungle Road site during the three-year monitoring period. The trends in the beginning of flow during the course of a year were the same as the trends the Jungle Road site, but the SP #1006 site had longer periods of continuous flow. For example, between January and May of 1995 the flow was continuous throughout the reach. In December 1995, flow began between 245 and 255 feet upstream from the reference point. These conditions continued until April 1996, when flow began at 445 feet from the reference point.

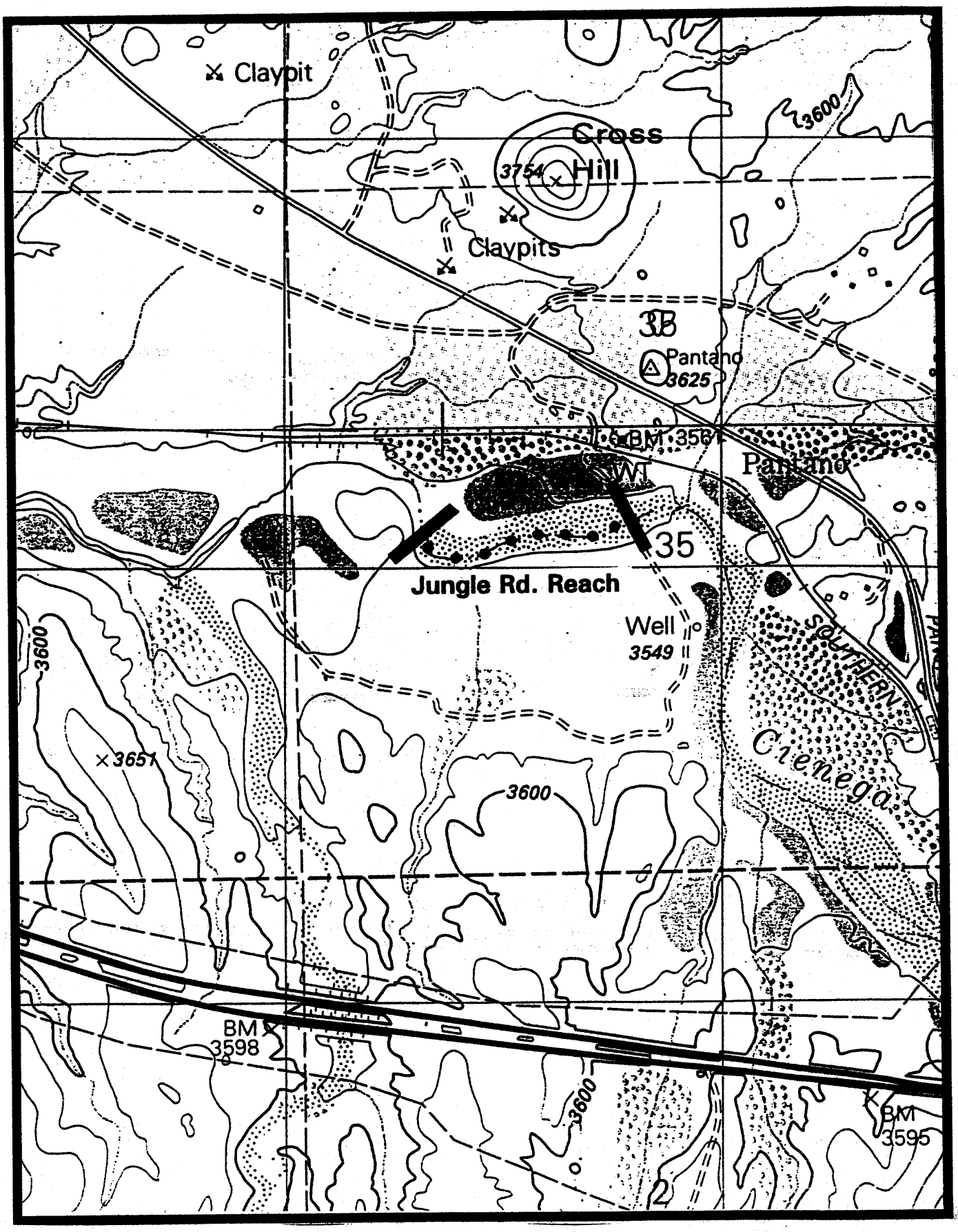
At the Davidson Creek site, there was little evidence to support a seasonal pattern to the fluctuations of the end-of-flow measurements during the three-year study period. After the first six months of the study, a pattern began to form which was similar to the pattern seen at the Jungle Road and SP #1006 sites. The end-of-flow migrated downstream during winter of 1994 and spring of 1995, indicating increasing flow. The seasonal variation continued through the summer of 1995 with movement of the end-of-flow measurements upstream, with no-flow conditions occurring in August 1995. For the eleven months following August of 1995 the flow was absent from the site. Flow returned abruptly during the fall of 1996, with rapid increases in the extent of flow occurring from September through November.

Seasonal patterns at the Davidson Creek site were probably obscured by the effects of the channel configuration on the discharge of groundwater to the surface. When PAG observed flow in Davidson Creek, it almost always emerged near a bedrock outcrop located 1,100 feet upstream from the Cienega confluence. This location is identified as a spring on the USGS Vail Arizona 7.5 minute quadrangle. During much of PAG's monitoring program, dense vegetation and thick deposits of sediment were present in the stream channel at this site. The vegetation and accumulated sediment typically formed a marsh and eliminated, or significantly reduced, the amount of surface flow extending downstream. As a result, measurements of how far downstream the flow extended did not always reflect the actual volume of water present at the surface. For example, PAG recorded "no flow" conditions along the Davidson reach on fourteen occasions, even though the site was only completely dry twice. Furthermore, sudden increases in the extent of flow were not always the result of significant, seasonal changes in meteorological or geohydrological conditions. In contrast, they were often the result of a single flood event scouring the channel and allowing more water to discharge from the site. This occurred between the August 1996 and September 1996 observations.

Comparing trends at the three sites using the distances measured from the photographs is difficult, because at the SP #1006 site, increasing distances mean increasing flow lengths, while at the other two sites, increasing distances mean decreasing flow lengths. Therefore, in order to compare trends at the three sites, PAG prepared a graph (Figure 28) showing, for each reach of interest, the percent of the reach that had continuous surface flow each month. To do this, the length of each reach of stream channel to be included in the analysis had to be defined. The reaches included in this analysis are shown on Figures 29, 30, and 31. For the Jungle Road site, the reach was defined as beginning at Jungle Road and extending 2,000 feet downstream, along the active channel of Cienega Creek. The 2,000-foot length was chosen because this is roughly the length of channel shown on the aerial photograph that PAG uses, and surface flow usually begins somewhere along this reach. For the Davidson site, PAG defined a 1,100-foot reach of Davidson Canyon extending upstream from the Cienega confluence. The 1,100-foot length was chosen because flow in this portion of Davidson

# Figure 28: Streamflow Observations
## Percent of Reach with Continuous Flow






N
W E
S

**Figure 29: Jungle Rd. Site**
**Defined Reach for Extent of Flow Percentage Analysis**

**1 inch = 1000 feet**

* Note: Base map is a photocopy of USGS 7.5 minute topographic maps for the Narrows and Rincon Peak Quadrangles.

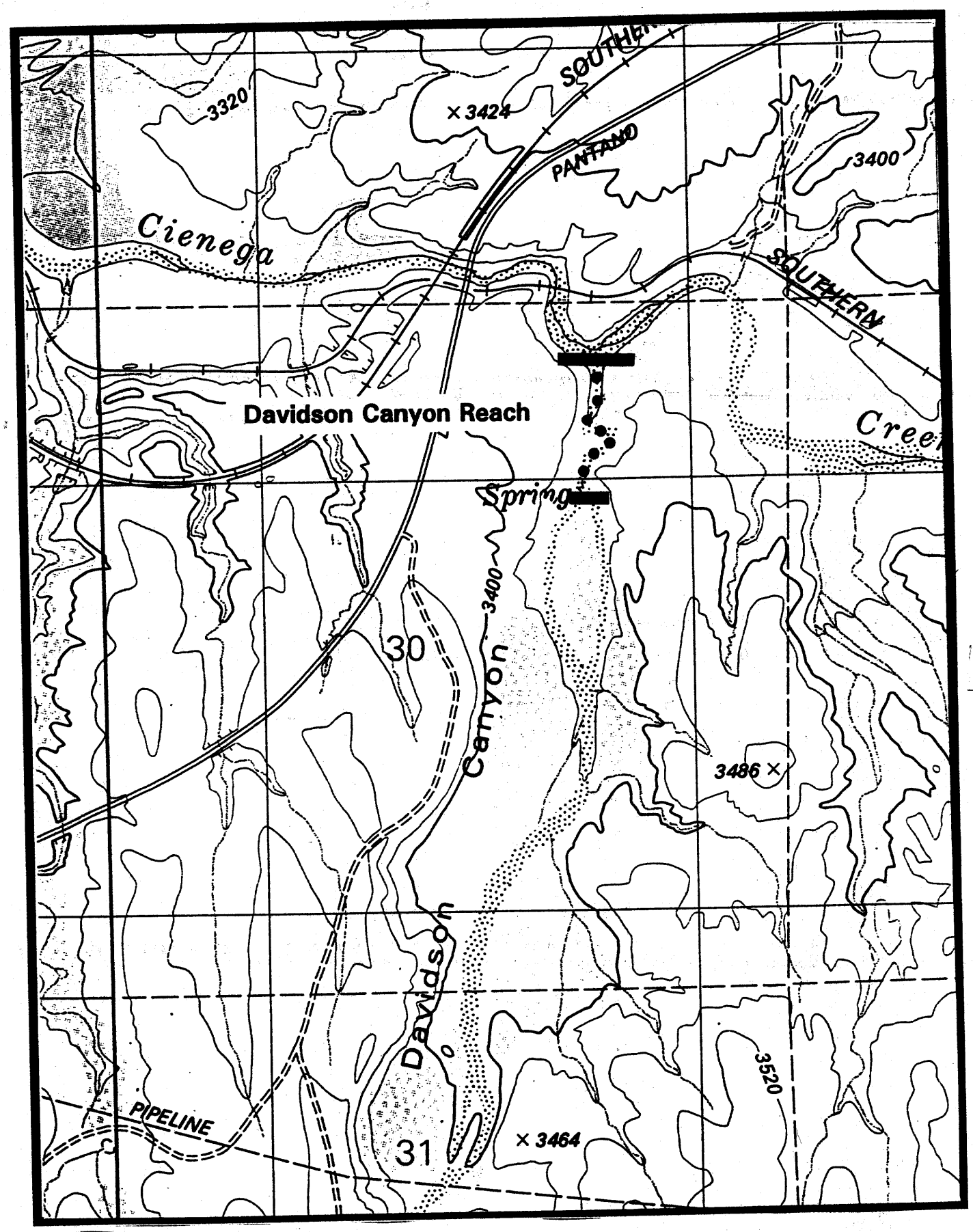



**Figure 30: Davidson Canyon Site**
**Defined Reach for Extent of Flow Percentage Analysis**

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W E
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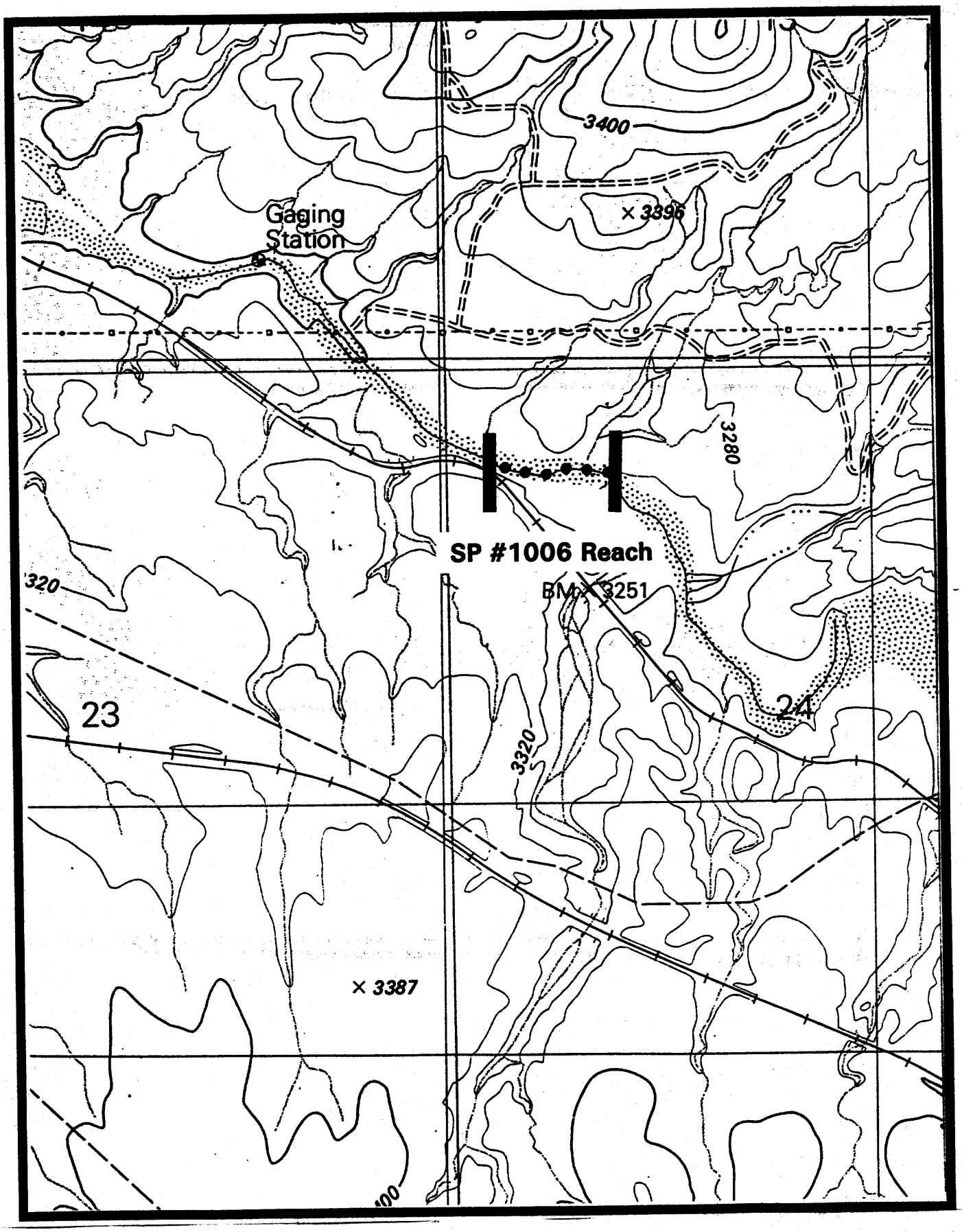
**1 inch = 1000 feet**

* Note: Base map is a photocopy of USGS 7.5 minute topographic map for the Vail Quadrangle.






N
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**Figure 31:** **SP #1006 Site**
**Defined Reach for Extent of Flow Percentage Analysis**

**1 inch = 1000 feet**

• Note: Base map is a photocopy of USGS 7.5 minute topographic map for the Vail Quadrangle.

Canyon usually begins at the spring associated with the bedrock outcrop described above (which is located 1,100 feet upstream from the confluence) and usually ends before reaching the confluence. For the SP #1006 site, PAG defined a 1,000-foot reach of Cienega Creek extending upstream from a point directly north of the SP #1006 mile marker. The 1,000-foot distance was chosen because surface flow in this area normally begins within 1,000 feet upstream of the reference point.

For each site, the percent of the designated reach that had continuous surface flow was calculated from the distances measured on the aerial photographs (Table 7) using the equations listed below. For example, at the Jungle Road site, if continuous flow in Cienega Creek began 1,000 feet downstream from the Jungle Road crossing, the percentage of the reach with continuous flow would be 50%, because the length of the reach is 2,000 feet. At the SP #1006 site, if flow began 750 feet upstream of the reference point, 75% of the reach would have flow. If no flow was present in a reach, R was assigned a value of zero, and if flow was continuous across the reach, R was assigned a value of 100%. The following equations were used:

Jungle Rd.: $R = [(2000 - x_J)/2000] * 100\%$
Davidson: $R = [(1100 - x_D)/1100] * 100\%$
SP1006: $R = [x_{SP}/1000] * 100\%$

where:

R = % of reach with flow
x = distances measured from aerial photographs and shown on Table 7:
$x_J$ = distance downstream from Jungle Rd to beginning of flow
$x_D$ = distance upstream from confluence to end of flow in Davidson
$x_{SP}$ = distance upstream from SP #1006 to beginning of flow

Figure 28 indicates that some trends in streamflow extent were consistent for all three sites. During the first year of record, all three sites showed a significant increase in streamflow extent during the winter and spring of 1994/1995, followed by a rapid decrease during the summer months of 1995. In addition, all three sites showed a decrease in extent of flow during the winter and spring of 1995/1996, compared to the previous winter. During the summer of 1996, all three sites showed dramatically lower extents of flow compared to the summers of 1994 and 1995. All three sites were dry on July 2, 1996.

Other trends were not consistent among the three sites. For example, peaks in streamflow extent were seen each September at the SP #1006 site, but not at the other sites. Also, increases in streamflow extent were seen during the spring of 1996 at Jungle Road and SP #1006, but the Davidson Canyon site continued to lack flow. Finally, streamflow extent at SP #1006 and Davidson rebounded significantly after the summer of 1996, but streamflow extent at Jungle Road did not.

During most of the 34 monthly observations that PAG made at each site, streamflow either began or ended within the reaches; only rarely did PAG observe either no-flow conditions or continuous flow across the reaches. The Jungle Road reach lacked flow on only five occasions (i.e., 14.7% of the time) and had continuous flow across the entire reach on only one occasion (2.9%), which was during a flood event. The Davidson Canyon reach lacked flow on 14 occasions (41.2%), was completely dry on two occasions (5.9%), and never had continuous

flow across the entire reach during PAG's visits. The SP #1006 site lacked flow on only one occasion (2.9%), which was in the middle of a significant drought, and had continuous flow across the entire reach on nine occasions (26.5%).

Comparison of Streamflow Extent to Precipitation Trends

PAG compared streamflow extent data to monthly precipitation data for the Cienega basin in order to evaluate how lower Cienega Creek and lower Davidson Creek responded to precipitation trends. For this analysis, streamflow extent for a given reach was measured as the percentage of the reach that contained continuous surface flow. Only base flows were included in the analysis; PAG's field observations were scheduled to avoid flood flows. The streamflow extent data were compared to the total precipitation for the previous month. PAG used precipitation data for Pima County Alert System (PCAS) gage 4280, located near the Interstate-10 crossing of Cienega Creek, for this comparison. Analysis of regional precipitation trends (Section III) showed a very strong correlation between precipitation data at various gages throughout the Cienega basin. Therefore, precipitation trends at PCAS gage 4280 should be fairly representative of precipitation trends throughout the basin.

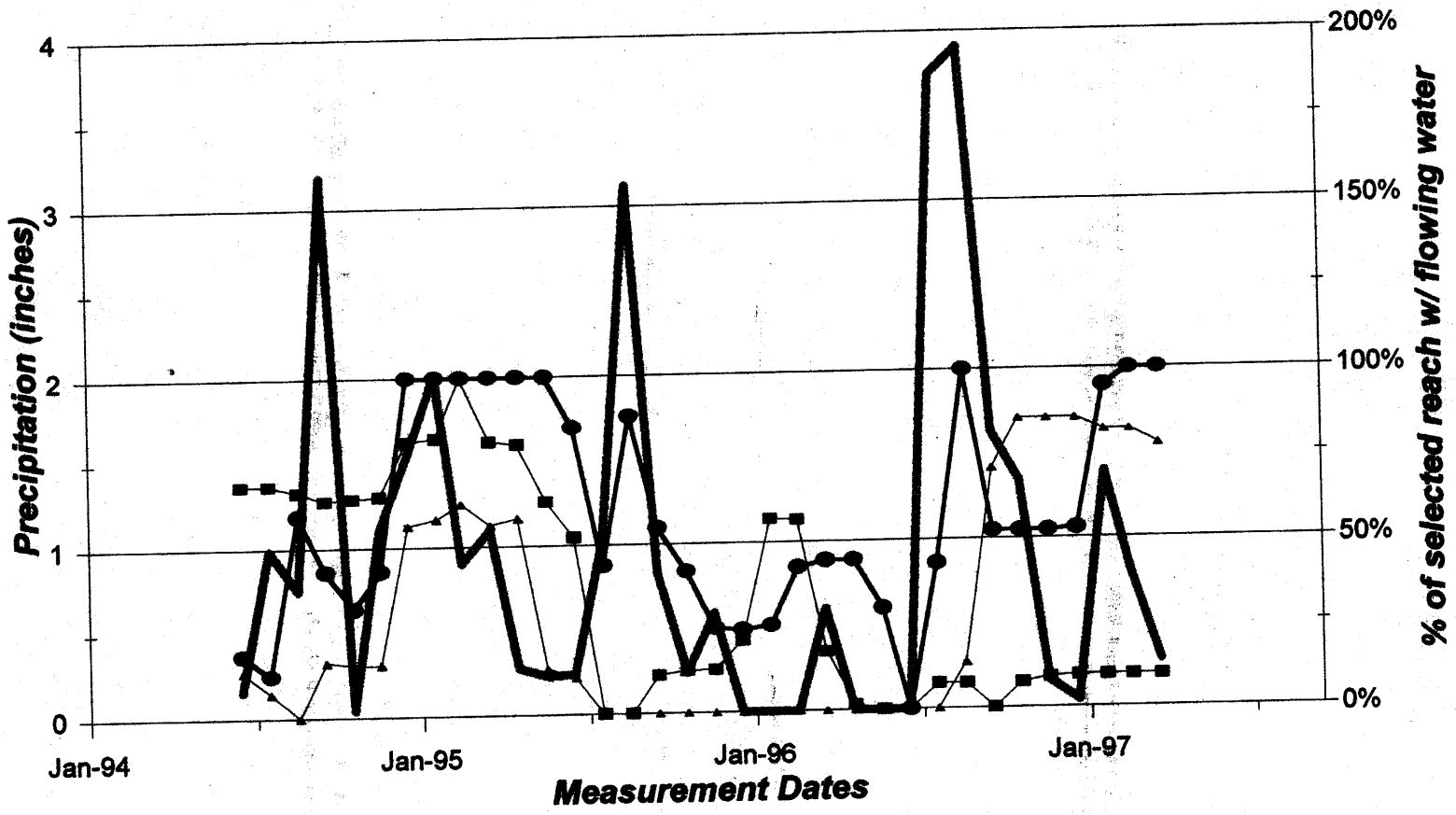
Figure 32 shows the relationship between streamflow extent and precipitation from July 1994 through April 1997. The graph shows that trends in streamflow extent at SP 1006 were similar to trends in precipitation. Most of the months with significantly increased rainfall showed corresponding increases in the extent of streamflow. However, streamflow extent did not always decrease in response to decreased monthly precipitation.

The extent of streamflow at Davidson Canyon showed varied responses to rainfall in the region. For example, the extent of streamflow decreased during and directly after the summer 1994 rains, and did not respond at all to rainfall received during 1995 and early 1996. However, rainfall received during the 1994/95 winter and the 1996 summer corresponded to increased flow extent. The variability in Davidson Canyon's response to precipitation was probably due partly to the channel configuration effects discussed in the previous section.

The extent of flow at the Jungle Road reach of Cienega Creek responded to most of the increases in monthly precipitation. However, the magnitude of the response usually was not proportional to the magnitude of the increase in rainfall. For example, monthly rainfall totals of one to two inches during the 1994-95 winter were followed by increases in streamflow extent to 80% or more, whereas monthly rainfall totals in excess of three inches during the 1996 summer thunderstorm season were accompanied by increases in streamflow to only 7.5%. In this case, the variable response to precipitation probably reflected the fact that winter storms are a more efficient mechanism for recharge than summer storms, which are typically high intensity and short duration. Other variations in the magnitude of the response might have been due in part to the suspected geologic constraints discussed in the previous section.

In addition to comparing temporal trends in streamflow extent and precipitation, PAG calculated correlation coefficients between streamflow extent data for each of the reaches and monthly precipitation data. The correlation coefficients were calculated by the spreadsheet program QuattroPro. A correlation coefficient of 0 indicates no correlation between the data sets, a correlation coefficient of 1 indicates a perfect positive correlation between the data sets, and a correlation coefficient of -1 indicates a perfect inverse correlation between the data sets. Correlation coefficients of -0.07, 0.01, and 0.30 were calculated

# Figure 32: Precipitation and Streamflow Extent vs.Time




Precipitation: PCAS Gage 4280
Streamflow Extent at Jungle Road
Streamflow Extent at SP 1006 Marker
Streamflow Extent at Davidson Cyn.

Data provided by Pima County Alert System database and original PAG research.

between monthly precipitation totals and streamflow extent data for the Jungle Road, Davidson, and SP 1006 sites, respectively, indicating that none of the sites showed a linear relationship between the extent of base flow and the previous month's precipitation. PAG also analyzed the relationship between streamflow extent and precipitation during the summer and winter months, but the correlation coefficients did not increase significantly for either season.

In summary, streamflow extent at the three sites in the lower Cienega basin monitored by PAG appeared to be related to precipitation during much of the period of record. However, the magnitude of the streamflow extent was not directly proportional to the magnitude of the monthly precipitation totals. The consistency with which streamflow extent responded to precipitation trends was probably limited by factors such as channel configuration and geologic constraints.

The reliability of these interpretations is limited by the relatively short period during which data have been collected. In addition, many potentially significant factors affecting how precipitation influences streamflow extent could not be addressed within the scope of this study. These factors include: intensity, location, and duration of individual precipitation events; variations in soil infiltration rates and aquifer transmissivities; and seasonal and geographical variations in evapotranspiration rates.

Stream Discharge Measurements

Methodology

PAG measured instantaneous stream discharge monthly at two locations along Cienega Creek in the Cienega Creek Natural Preserve: the Marsh Station Bridge site and the Tilted Beds site (Figure 33). The Tilted Beds site is located in section 34 of Township 16 South, Range 17 East, two miles downstream from Interstate 10. The site is a little over one-half mile downstream from the Jungle Road crossing, where perennial streamflow in the preserve usually begins. The Marsh Station Bridge site is located in the southern end of section 19 of Township 16 South, Range 17 East, roughly six and a half miles downstream from Interstate 10, and slightly less than a quarter mile downstream from Davidson Canyon's confluence with Cienega Creek.

Measurements began in June 1993 at the Marsh Station Bridge site and in July 1994 at the Tilted Beds site. PAG usually measured the discharge during the first week of each month. In some months, however, the measurements could not be made, or they had to be rescheduled, due to equipment failure or flooding. PAG attempted to measure only the base flows in the creek so that the data would be relatively consistent, allowing long-term trends in "normal" conditions to be observed. Therefore, PAG tried to avoid conducting the measurements immediately after precipitation events which produced flood flows. Due to the unpredictable nature of the region's climate, however, this was not always possible, and a few of the measurements included flood flow. Both stations were usually measured on the same day each month.

PAG used a Qualimetrics brand, Model 6660 digital water current meter for the discharge measurements at the Marsh Station Bridge site. Discharge was calculated from velocity and depth measurements made at equally-spaced intervals across the stream channel. This method was also employed at the Tilted Beds site, but the stream velocities at the Tilted Beds site were often too low to be accurately measured. Therefore, most discharge

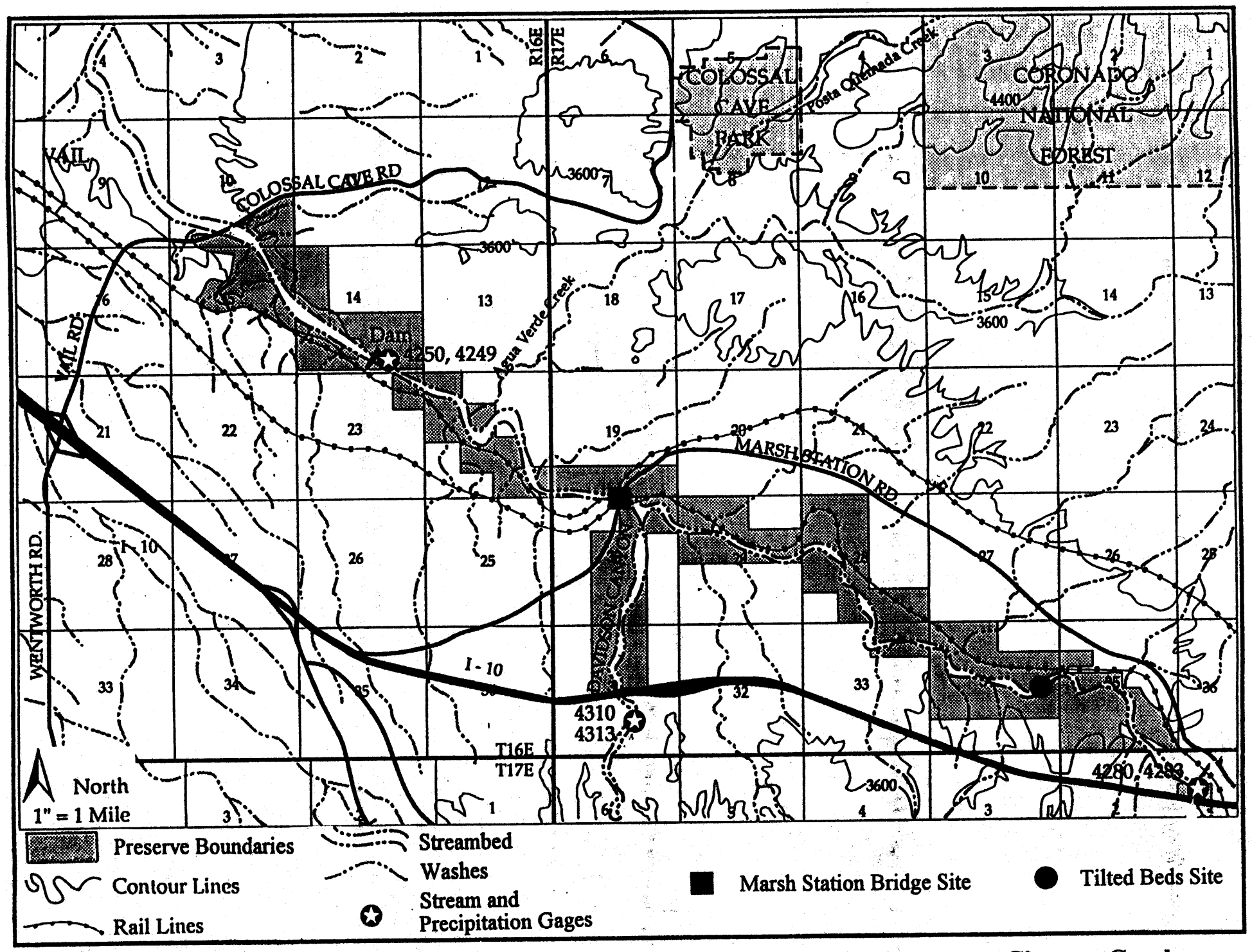



**Figure 33: Locations of Instantaneous Stream Discharge Measurements on Cienega Creek**

* Note: Base map provided to PAG by Pima County Flood Control District

measurements at the Tilted Beds site were made by catching the flow from a small waterfall in a 22-quart bucket. The volume collected and the time required for the volume to be collected were measured. The waterfall usually included most, if not all, of the discharge, and any remaining discharge was diverted into the waterfall with rocks and sand. PAG also purchased a Free Flow brand, large 60° V-Notch Trapezoidal flume in June 1996 for measurements at the Tilted Beds site when neither the flow meter nor bucket method could be used. Use of the flume has not been necessary thus far.

Results

Table 8 summarizes the results of PAG's Cienega Creek instantaneous discharge measurements at Tilted Beds and Marsh Station bridge. Discharge was consistently greater at Marsh Station bridge than at the Tilted Beds site, indicating that this reach was predominantly a gaining stream. The average base flow was 1.46 cubic feet per second (cfs) at Marsh Station bridge and 0.10 cfs at Tilted Beds. Maximum recorded flows were 12.1 cfs at Marsh Station and 9.5 cfs at Tilted beds on March 7, 1995, but these represented flood flows. Maximum recorded base flows were 4.36 cfs at Marsh Station and 0.46 cfs at Tilted Beds on January 10, 1995. Minimum recorded flows were 0.38 cfs at Marsh Station bridge on July 2, 1996, and 0 cfs at Tilted Beds on July 2, 1996 and June 5, 1996. These were recorded during a moderate to severe drought (Figure 6).

Monthly instantaneous discharge measurements through April 1997 are illustrated on Figures 34 and 35 for Tilted Beds and Marsh Station, respectively. Significant seasonal variation was seen at both sites, with the highest base flows occurring from December through April and the lowest base flows occurring from June through August. A short-term increase in discharge was consistently seen in September, presumably in response to summer rains.

As shown by Figures 34 and 35, seasonal trends were highly consistent between the two sites. Figure 36 is an x-y scatter plot of Marsh Station base discharge versus Tilted Beds base discharge, along with a best-fit line and a correlation coefficient ("R" value). The correlation coefficient and best-fit line were calculated by the QuattroPro spreadsheet that was used to create the graphs. The Marsh Station and Tilted Beds data were fairly closely correlated (R=0.77), indicating that higher and lower base flows at Tilted Beds were typically associated with higher and lower base flows at Marsh Station. The moderate scattering of points away from the best-fit line was probably due to error associated with the different measurement techniques, particularly during low-flow conditions, and to influences from springs and tributaries (such as Davidson) between the sites. The flood flows of March 1995 were not included on the graph or in the calculation of the correlation coefficient shown on the graph. A correlation coefficient of 0.94 was calculated for the data with the flood flows included.

## Table 8. Discharge at Tilted Beds and Marsh Station Sites

| Month/Year | Tilted Beds Site Q (cfs) | Marsh Station Site Q (cfs) | | Month/Year | Tilted Beds Site Q (cfs) | Marsh Station Site Q (cfs) |
|---|---|---|---|---|---|---|
| 7/1/93 | No data | No data | | 6/5/95 | 0.10 | 1.44 |
| 8/1/93 | No data | 1.13 | | 6/29/95 | 0.04 | 0.83 |
| 9/1/93 | No data | 5.80 | | 8/3/95 | 0.03 | 0.53 |
| 10/7/93 | No data | 0.88 | | 9/1/95 | 0.09 | 0.85 |
| 11/4/93 | No data | 1.02 | | 10/4/95 | 0.04 | 0.64 |
| 12/7/93 | No data | 2.16 | | 11/1/95 | 0.06 | 0.59 |
| 1/1/94 | No data | No data | | 12/4/95 | 0.08 | 1.04 |
| 2/2/94 | No data | 3.04 | | 1/9/96 | 0.10 | 1.50 |
| 3/3/94 | No data | 3.24 | | 2/1/96 | 0.11 | 1.64 |
| 4/1/94 | No data | No data | | 3/8/96 | 0.07 | 1.91 |
| 5/4/94 | No data | 2.25 | | 4/4/96 | 0.07 | 1.90 |
| 6/2/94 | No data | 1.27 | | 5/2/96 | 0.06 | No Data |
| 7/8/94 | 0.10 | 0.56 | | 6/5/96 | 0.0 | 0.56 |
| 8/5/94 | <0.1 | 0.4 | | 7/2/96 | 0.0 | 0.38 |
| 9/9/94 | 0.11 | 1.07 | | 8/2/96 | 0.04 | 0.49 |
| 10/5/94 | 0.07 | No data | | 9/5/96 | 0.11 | 1.38 |
| 11/4/94 | 0.13 | 0.91 | | 10/8/96 | 0.02 | 1.09 |
| 12/1/94 | 0.22 | 1.77 | | 11/6/96 | 0.06 | 1.27 |
| 1/10/95 | 0.46 | 4.36 | | 12/5/96 | 0.06 | 1.80 |
| 2/1/95 | No data | No data | | 1/9/97 | 0.07 | 2.14 |
| 3/7/95 | 9.50 | 12.10 | | 2/13/97 | 0.07 | 1.86 |
| 4/6/95 | 0.36 | 2.43 | | 3/7/97 | 0.08 | 2.07 |
| 5/4/95 | 0.24 | 1.86 | | 4/7/97 | 0.04 | 1.63 |

Relationship to Streamflow Extent

PAG compared discharge data with streamflow extent data to determine whether discharge at Tilted Beds and Marsh Station were correlated with flow extent at Jungle Road, Davidson Canyon, and SP 1006. In addition to reviewing the time-series graphs to identify consistent trends, PAG reviewed x-y scatter graphs and calculated correlation coefficients using the spreadsheet program QuattroPro. The results are shown on Table 9. A correlation coefficient of 1 indicates a perfectly linear correlation; a value of 0 indicates no correlation.

A reasonably good relationship between base discharge at the Tilted Beds site and streamflow extent at the Jungle Road site was noted, with seasonal increases and decreases in flow extent and discharge generally coinciding. However, some significant inconsistencies between flow extent and discharge were noted. For example, between September 1994 and September 1996, a net drop in streamflow extent of 59% was observed at the Jungle Road site, while no significant net change in discharge was seen at Tilted Beds. A correlation value of 0.69 was calculated between the data sets, with the highest (and lowest) discharge rates usually corresponding to the highest (and lowest) flow extents. A good correlation was expected, because both sites were on Cienega Creek, and Tilted Beds was only about one-half mile downstream from the Jungle Road site. However, the correlation was probably somewhat limited by the suspected geologic controls on the extent of flow at the Jungle Road site, which caused the points on the graph to be clustered near 10% and 65% along the x-axis.

**Figure 34: Cienega Creek Streamflow at Tilted Beds Site**

Discharge vs. Time

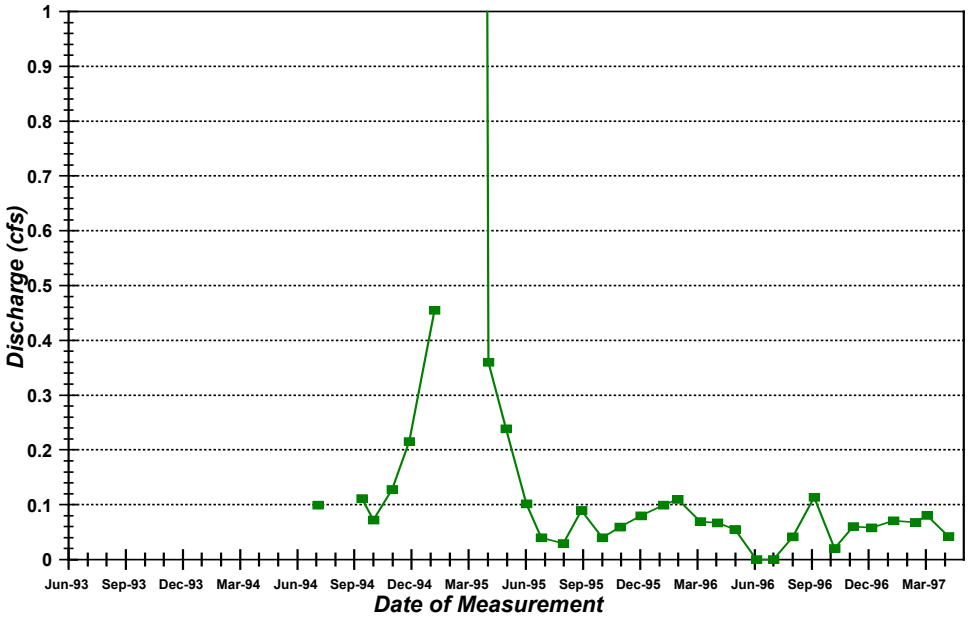



**Figure 35: Cienega Creek Streamflow at Marsh Station Site**

Discharge vs. Time

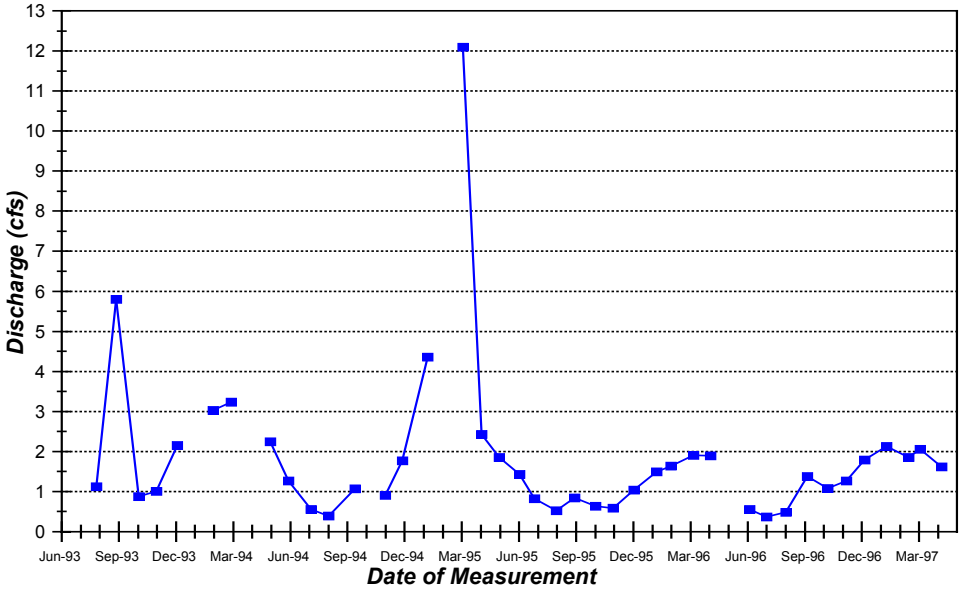


**Figure 36: Cienega Creek Streamflow**

Marsh Station Discharge vs. Tilted Beds Discharge

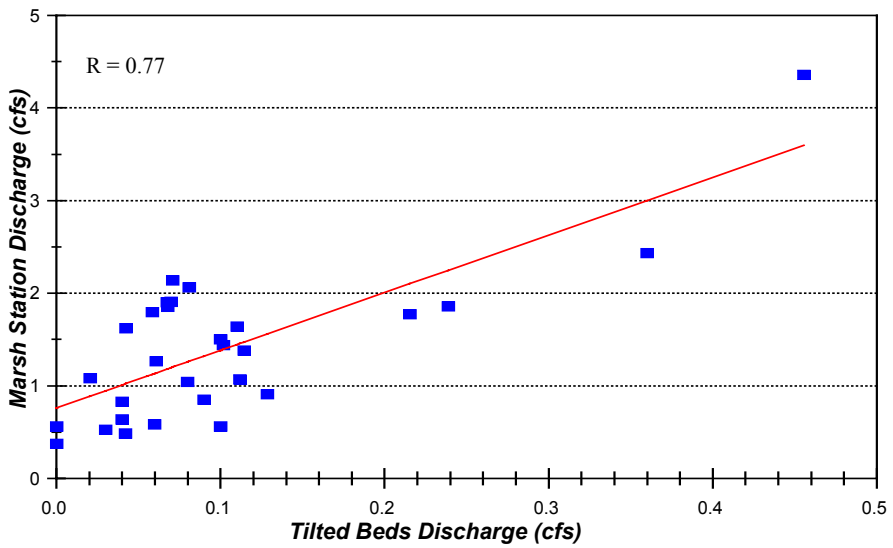



**Table 9. Relationship between Stream Discharge and Streamflow Extent**

| Discharge Monitoring Site | Flow Extent Monitoring Site | Correlation Value (R) |
|---|---|---|
| Tilted Beds | Jungle | 0.69 |
| Marsh Station | Jungle | 0.36 |
| Marsh Station | Davidson | 0.52 |
| Marsh Station | SP 1006 | 0.54 |

Seasonal increases and decreases in discharge at Marsh Station appeared to coincide, in most cases, with seasonal trends in flow extent at Jungle Road, Davidson Canyon, and SP 1006; however, several inconsistencies were apparent. As a result, the correlation coefficients were fairly low, ranging from 0.36 for the Jungle Road site to 0.54 for the SP 1006 site. The lack of correlation with the Jungle Road site was probably due to the distance between the sites (about 5 miles), influences from tributaries, and the geologic controls at the Jungle Road site. The correlation coefficient was slightly higher for Davidson Canyon (R = 0.52) than for Jungle Road, indicating that discharge at the Marsh Station site might have been influenced by conditions in lower Davidson Canyon.

PAG did not compare Tilted Beds discharge to flow extent at Davidson or SP1006, because Marsh Station was closer to these sites, and therefore more suitable for evaluating the consistency between discharge and flow extent.

Relationship to Precipitation Trends

PAG compared stream discharge data for the Tilted Beds and Marsh Station sites to monthly precipitation data for the Cienega basin in order to evaluate how lower Cienega Creek responded to precipitation trends. The analysis focused on base flows, although some flood flows were included. Discharge data collected during the first week of each month were compared to the total precipitation recorded during the previous month. PAG used precipitation data for Pima County Alert System (PCAS) gage 4280, located near the Interstate-10 crossing of Cienega Creek, for this comparison. Analysis of regional precipitation trends (Section III) showed a very strong correlation between precipitation data at various gages throughout the Cienega basin. Therefore, precipitation trends at PCAS gage 4280 were assumed to be fairly representative of trends throughout the basin.

Figure 37 shows the relationship between precipitation and stream discharge at the Marsh Station site from June 1993 through April 1997. The graph shows discharge values measured during the first week of each month, and the total precipitation recorded at PCAS gage 4280 during the previous calendar month.

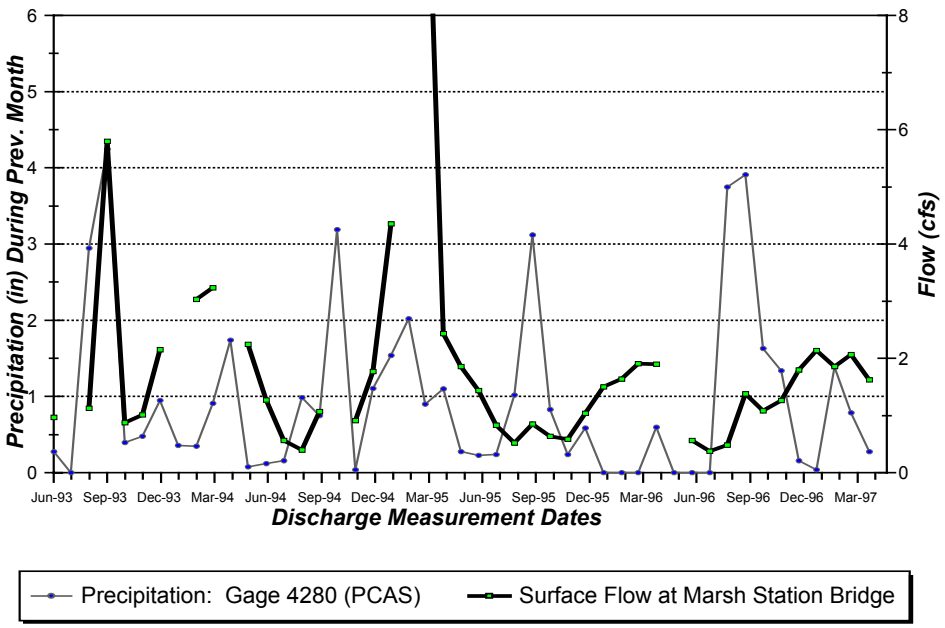
The graph indicates that monthly precipitation totals and Cienega Creek base flows at Marsh Station Bridge often followed similar trends. As expected, periods of low discharge were clearly related to periods of low precipitation. The lowest monthly discharge values appeared to follow lows in monthly precipitation totals by about two to three months. The lowest monthly precipitation totals were usually recorded in April, May and June; the lowest base flows were usually recorded in July and August.

The relationship between periods of high discharge and high precipitation was not as clear. The largest discharge peaks, which were measured in September 1993 and March 1995, align with peaks in monthly precipitation totals for the previous month. However, these discharge values represent flood flows, and do not provide any information about the base flow response. The more moderate, regularly-occurring peaks in streamflow reflect increases in base flow. In some cases, including December 1993 and December 1994, base flow increased within one month of an increase in monthly precipitation totals. This suggests a fairly short response time. In other cases, including the periods of August 1995 through March 1996 and August 1996 through March 1997, the relationship between base flows and precipitation was less clear. During these periods, minor, short-term increases in stream discharge, particularly in September, appeared to coincide with peaks in monthly precipitation totals. The minor discharge peaks were followed by larger, longer-term discharge peaks that were recorded several months after the peaks in precipitation were recorded.

A plausible explanation for these observations is that the minor peaks in September reflected base flow responses to summer precipitation, which tends to be intense, localized, and of a short duration, and thus not particularly efficient for groundwater recharge. The base flow response to this recharge might also have been damped by high evapotranspiration (ET) rates. Thus, the larger, winter-season discharge peaks likely reflected a decrease in ET, rather than a delayed response to precipitation events. Groundwater level data for the Cienega and Del Lago #1 wells for the same period (Figures 22 and 23) support this hypothesis. Water level data for the Cienega well also showed minor peaks in September, followed by longer-term rises, which suggests that the discharge trends were due to fluctuations in groundwater-derived base flows. The fact that a water level rise occurred at the Cienega well and not the Del Lago #1 well between November 1995 and April 1996, when unseasonably low monthly precipitation

**Figure 37: Precipitation and Stream Discharge vs. Time**

Gage 4280 (PCAS) and Marsh Station Site




Data from Pima County Alert System database and PAG field measurements.

totals were recorded, provides additional support for the hypothesis that ET affected the stream discharge trends, because diurnal measurements conducted by PAG (see Section VII) indicated that groundwater levels at the Cienega well fluctuated in response to changes in ET rates, whereas groundwater levels at the Del Lago #1 well did not.

Another possible explanation is that the minor peaks in base flows were the result of short-term recharge of shallow streambed alluvial deposits in the immediate vicinity of the measuring points, and that the larger peaks represented a delayed response to recharge that occurred on a more regional scale. However, no delay between the precipitation events and groundwater level rises at the Cienega well was observed during the periods in question, which indicates that this explanation is probably not valid.

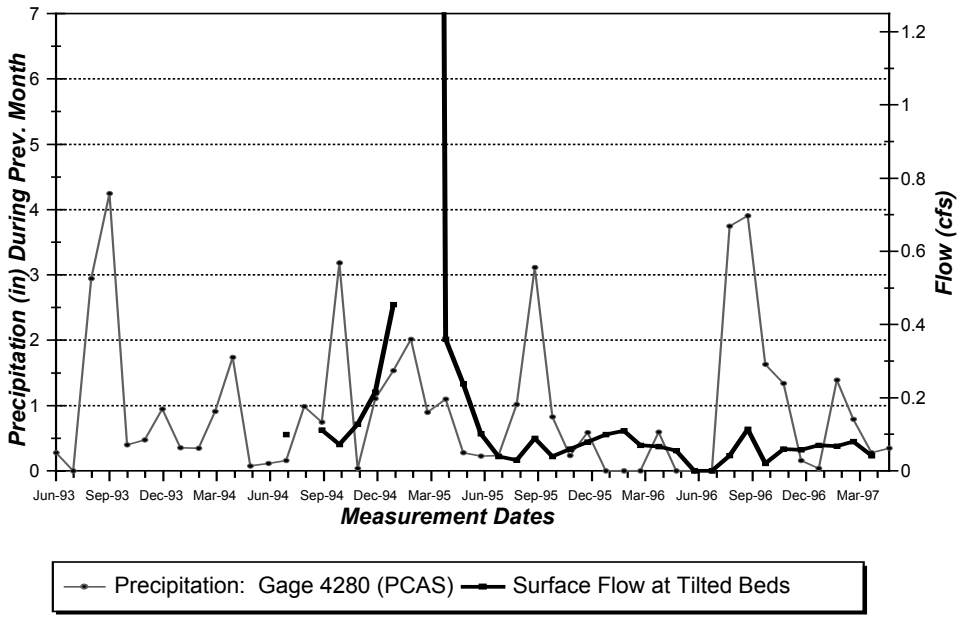
A third explanation is that the smaller peaks were due to some runoff from recent precipitation events being included in the measurements, and that the base flow did not respond until the larger peaks were recorded. However, runoff events are usually fairly brief, particularly during the summer months. Also, as noted above, the Cienega well data showed that groundwater levels followed a trend very similar to stream discharge, which suggests that the discharge trends were due to fluctuations in groundwater-derived base flows, and not runoff.

Figure 38 shows the relationship between precipitation and stream discharge at the Tilted Beds site from July 1994 through April 1997. The relationship was similar to the relationship seen between the Marsh Station data and precipitation. Some peaks in discharge at Tilted Beds appeared to occur within one month of an increase in monthly precipitation, while other discharge peaks showed a lag of two or three months. In addition, minor peaks occurred

in September 1995 and September 1996, roughly concurrent with increases in precipitation. Discharge lows usually occurred within one or two months of monthly precipitation lows.

**Figure 38: Precipitation and Stream Discharge vs. Time**

Gage 4280 (PCAS) and Tilted Beds Site




Data from Pima County Alert System database and PAG field measurements.

In addition to comparing temporal trends in stream discharge and precipitation, PAG calculated correlation coefficients between stream discharge and monthly precipitation totals. The correlation coefficients were calculated by the spreadsheet program QuattroPro. Flows greater than 5 cfs were excluded from the calculation so that the analysis only included base flows. Correlation coefficients of -0.05 and 0.09 were calculated between precipitation and discharge at Marsh Station and Tilted Beds, respectively, indicating that a linear relationship did not exist between the base discharge measured during the first week of a month and the amount of precipitation recorded during the previous month. The correlation did not improve significantly when the data were compared on a seasonal basis.

The lack of correlation might have been due in part to lag times between some precipitation trends and discharge trends. Somewhat higher correlation coefficients (0.30 for Marsh Station and 0.37 for Tilted Beds) were calculated when a three-month lag time between precipitation and discharge was applied. However, these values were not high enough to indicate a linear relationship between discharge and monthly precipitation totals. Also, these data were not sufficient evidence to conclude that three months is the average lag time between precipitation trends and streamflow response.

PAG also compared trends in Cienega Creek base discharge to trends in temperatures, which, along with other factors, should reflect trends in evapotranspiration. Somewhat of an inverse relationship was observed between temperature and base flow, with peaks in base flow often occurring during or shortly after periods of low monthly maximum temperatures, and lows

in base flow often occurring during periods of high temperature. Correlation coefficients of -0.46 and -0.36 were calculated between average monthly temperatures and discharge at Marsh Station and Tilted Beds, respectively, for a two-month lag time, and -0.51 and -0.18 for a three-month lag time. The absolute values of these correlation coefficients are similar to values calculated between precipitation and discharge, suggesting that base flows in the creek respond not only to increases (and decreases) in precipitation, but also to decreases (and increases) in evapotranspiration.

In summary, trends in base flows in lower Cienega Creek appeared to roughly reflect trends in precipitation. However, the response time to precipitation trends, as well as the magnitude of the response, appeared to be somewhat variable. Differences in the magnitude of response were probably due in part to differences in intensity and duration of summer and winter precipitation events. Seasonal variations in evapotranspiration rates probably had a significant effect on trends in base flows as well.

PAG's interpretations are based on less than four years of data for only two discharge monitoring points. More discharge and precipitation data are needed to adequately assess the relationship between lower Cienega Creek discharge and precipitation trends. In addition, information regarding the intensity, location, and duration of individual precipitation events, variations in infiltration rates and transmissivities, and seasonal and geographical variations in evapotranspiration rates and are needed to gain a thorough understanding of the relationship between precipitation and stream discharge.

# VI. COMPARISON OF GROUNDWATER TRENDS TO SURFACE WATER TRENDS

PAG evaluated the relationship between surface water and groundwater by comparing graphs of groundwater level data with graphs of streamflow extent and stream discharge. The analysis was based on the period from July 1994, when the current surface water monitoring program began, through April 1997.

## Streamflow Extent and Groundwater Trends

Figures 39 through 54 are three sets of graphs comparing streamflow extent to depth to groundwater. One set of graphs was prepared for each of the streamflow-extent monitoring sites: Jungle Road, Davidson, and SP1006. For each streamflow-extent monitoring site, one series of graphs plots streamflow extent (as % of reach with flow) and depth-to groundwater at a nearby well simultaneously versus time. Each of these graphs is followed by an x-y scatter graph showing streamflow extent versus depth to water at a nearby well. The x-y scatter graphs include best-fit lines and correlation coefficients that were calculated by QuattroPro.

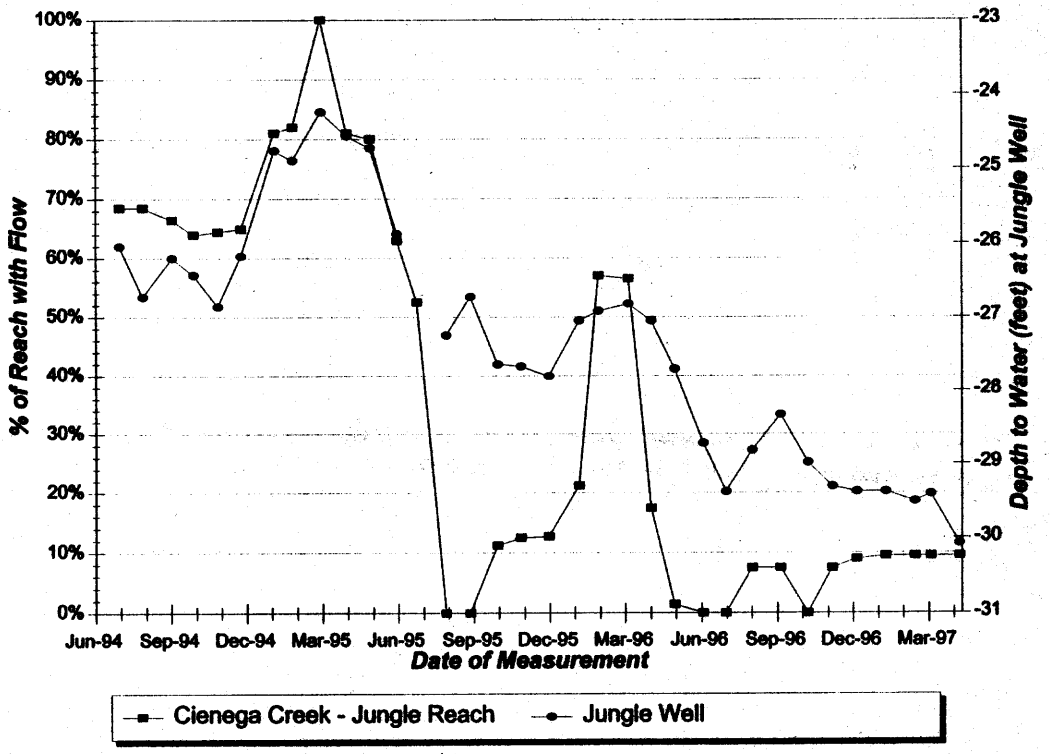
### Jungle Road Reach

A good correlation (R = 0.86) was seen between streamflow extent along the Jungle Road reach of Cienega Creek and groundwater levels at the Jungle well, which was in the immediate vicinity of the observed reach (Figures 39 and 40). Seasonal trends in streamflow extent along the Jungle Road reach were very consistent with seasonal trends in depth-to-water at the Jungle well, indicating that groundwater and surface water systems in this area were highly interconnected. Water level rises and streamflow extent increases occurred in the winter of 1994-1995, the winter of 1995-1996, and the fall of 1996. Each of these rises was followed by a rapid decline. An overall decline in groundwater levels (from about 26 feet to 30 feet) and streamflow extent (from about 65% to 10%) was apparent between July 1994 and April 1997. In general, when groundwater levels at the Jungle well were deeper than 28 feet bls, less than 10% of the reach had surface flow; when water level depths at the well were less than 27 feet bls, more than 50% of the reach usually had surface flow. An exception was noted in September 1995, however, when the Jungle Road reach lacked flow yet the groundwater depth at the Jungle well was less than 27 feet bls.

A high degree of correlation (R=0.79) was also seen between the Jungle Road streamflow site and the upgradient Empirita #1 well (Figures 41 and 42). An overall decline in water levels of about 8 feet occurred at the Empirita #1 well, consistent with the overall decrease in streamflow extent at the Jungle Road site. In general, when groundwater levels at Empirita #1 were deeper than 24 feet bls, less than 20% of the Jungle Road reach had surface flow. In most cases, when water level depths at Empirita #1 were less than 24 feet bls, at least 50% of the reach had flow. Exceptions were observed in August and September 1995, however, when the reach lacked surface flow yet depth to water at Empirita #1 was less than 22 feet bls.

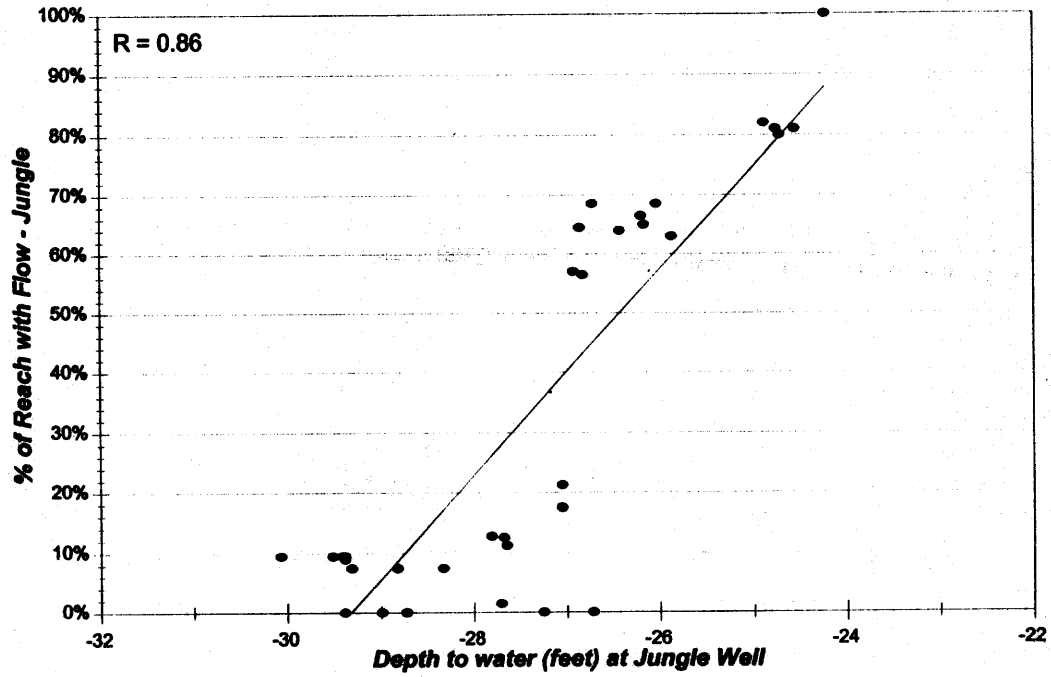
## Figure 39: Groundwater/Surface Water Relationship

Jungle Reach and Jungle Well vs. Time



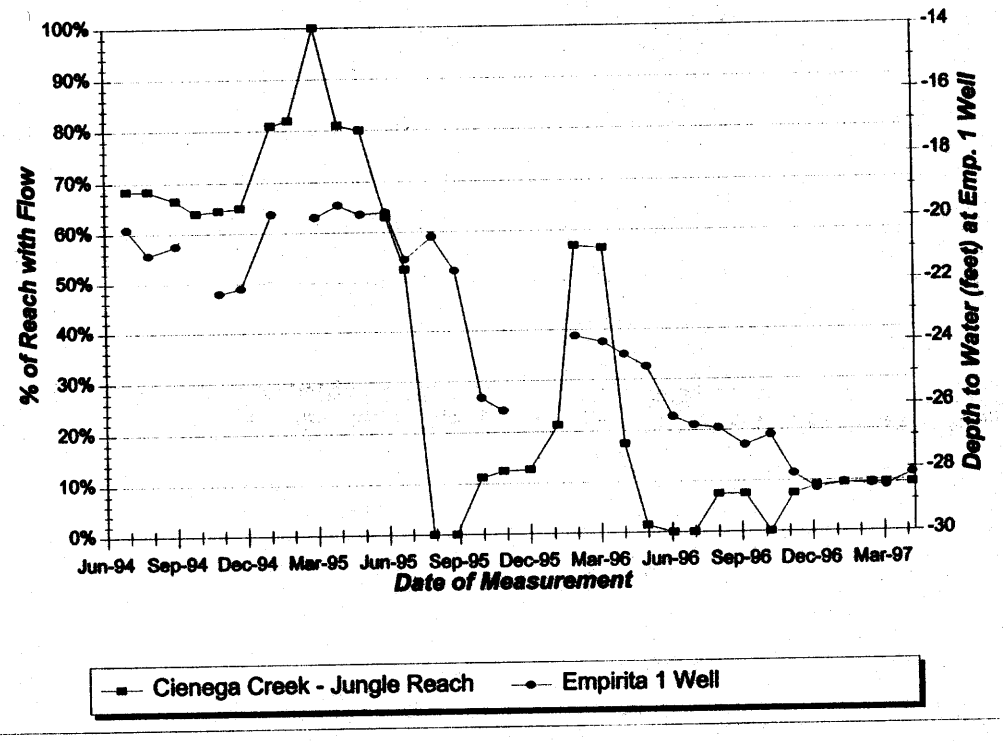

## Figure 40: Groundwater/Surface Water Relationship

Jungle Reach vs. Jungle Well



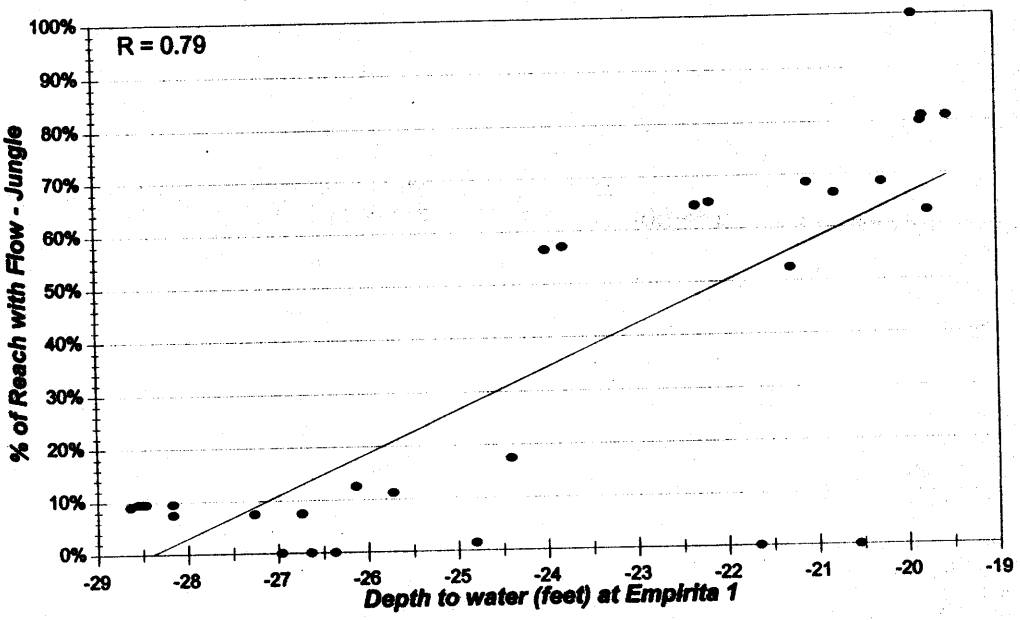
## Figure 41: Groundwater/Surface Water Relationship

Jungle Reach and Empirita 1 Well vs. Time




## Figure 42: Groundwater/Surface Water Relationship

Jungle Reach vs. Empirita 1 Well



Most seasonal increases and decreases in streamflow-extent at the Jungle Road site coincided with rises and falls in groundwater levels at the Cienega well (Figure 43), located about two miles downstream. However, the overall decline in streamflow extent along the Jungle Road reach was not reflected in the water level data for the Cienega well. Also, although the trends coincided, the magnitudes of the trends were not consistent, especially after the summer of 1996. In addition, water levels in the well tended to recover more quickly than streamflows at Jungle Road. In general, as shown on Figure 44, both low-flow conditions (i.e., flow extent < 10%) and high-flow conditions (i.e., flow extent > 50%) were observed for a wide range of groundwater levels. The correlation coefficient calculated for the data was low, at 0.38. The lack of correlation was probably due at least in part to the presence of a bedrock high at Tilted Beds, which presumably limits the extent to which the sites are hydrologically interconnected.

Groundwater levels at Empirita #2 and streamflow extent at Jungle Road did not appear to be correlated (Figures 45 and 46). The data did not follow similar trends, with the possible exception of a water level rise at Empirita #2 which followed an increase in flow extent at Jungle Road in the spring of 1996. The correlation coefficient for the data was only 0.41. Empirita #2 is a deep well with perforations only in the Pantano formation; it does not tap water from the alluvial deposits (Errol Montgomery and Associates, 1985).

Streamflow extent at the Jungle Road site was not compared to water levels at the Del Lago #1 well because the Del Lago #1 well is more than seven miles downstream. Analysis of the Cienega well data was deemed sufficient for evaluating the relationship with downstream water levels.

Davidson Reach

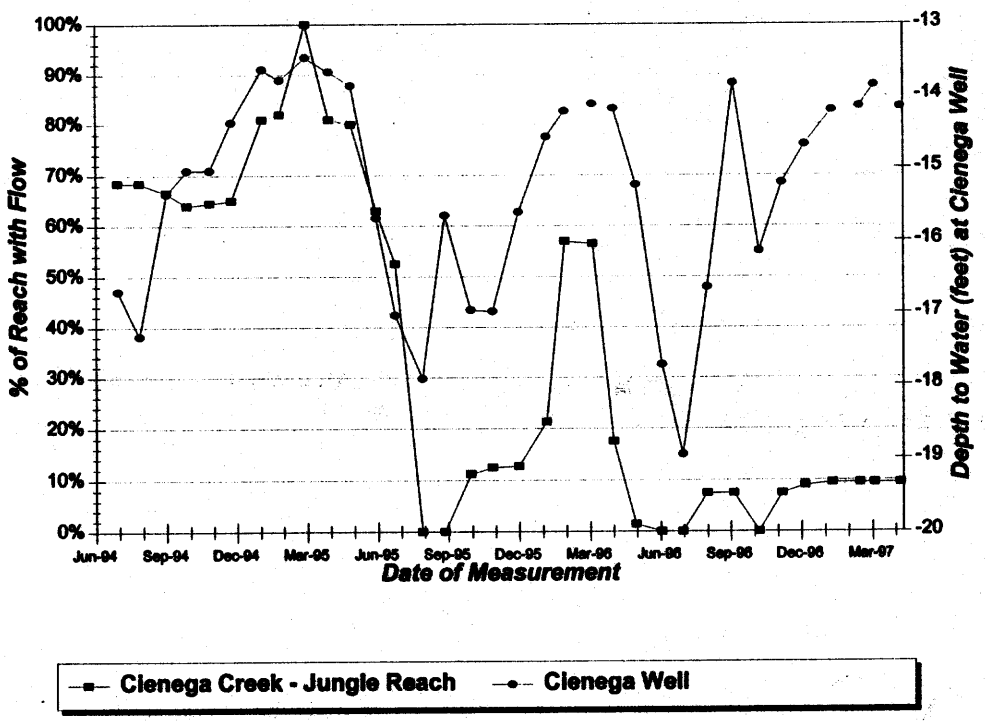
Streamflow extent at PAG's monitoring site in lower Davidson Canyon was compared to groundwater levels in the Cienega well (Figures 47 and 48) and Del Lago #1 well (Figures 49 and 50). Analyses were not made for the Jungle, Empirita #1 and Empirita #2 wells, because they were more than five miles upstream. Analysis of the Cienega well data was deemed sufficient for evaluating the relationship between flow extent in lower Davidson Canyon and water levels upstream along Cienega Creek.

As shown on Figure 47, streamflow extent at the Davidson site often followed trends similar to trends in groundwater levels at the Cienega well. However, several notable exceptions were observed, particularly during the winter and spring of 1995-96, when the Davidson reach lacked flow but groundwater levels at the Cienega well were fairly shallow. At other times, including August - September 1994 and July-August 1996, a one-month lag was observed between groundwater level rises in the Cienega well and subsequent streamflow-extent increases in lower Davidson Canyon.

As shown by Figure 48, a linear relationship between streamflow extent at the Davidson site and groundwater levels at the Cienega well was not observed (R = 0.52). In general, high-flow conditions (i.e., streamflow extent > 50%) were only observed when groundwater depths were less than 16 feet bls, but low-flow conditions (i.e., streamflow extent < 20%) were observed over the complete range of groundwater levels that were measured at the Cienega well. The lack of a linear relationship was probably due largely to the marsh in Davidson Canyon, which often acted as a storage reservoir by preventing streamflow from extending downstream.

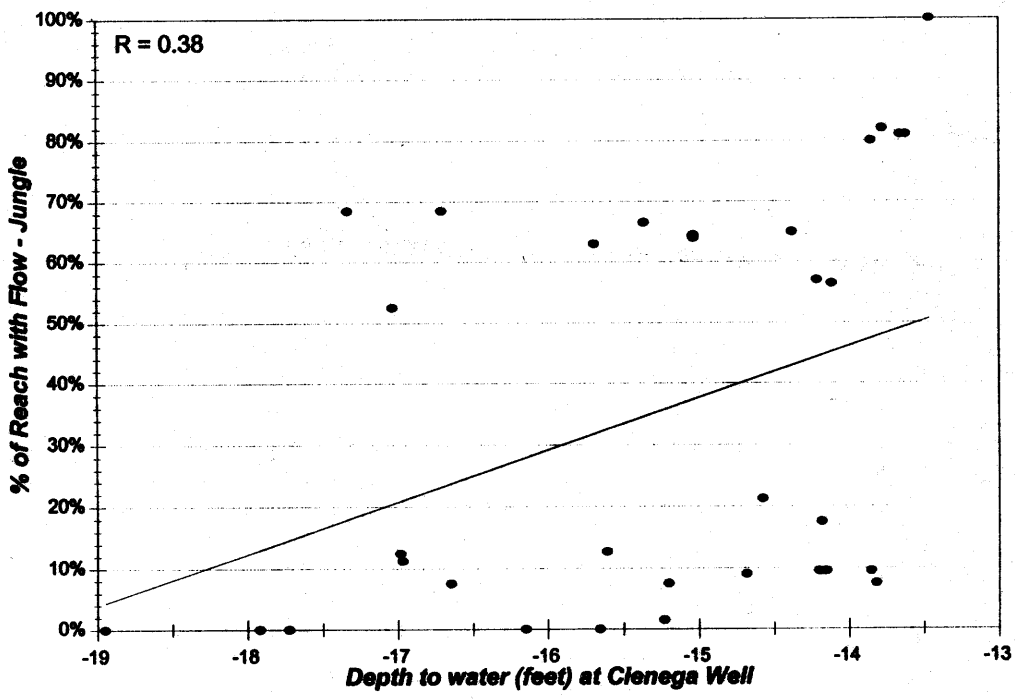
## Figure 43: Groundwater/Surface Water Relationship

Jungle Reach and Cienega Well vs. Time



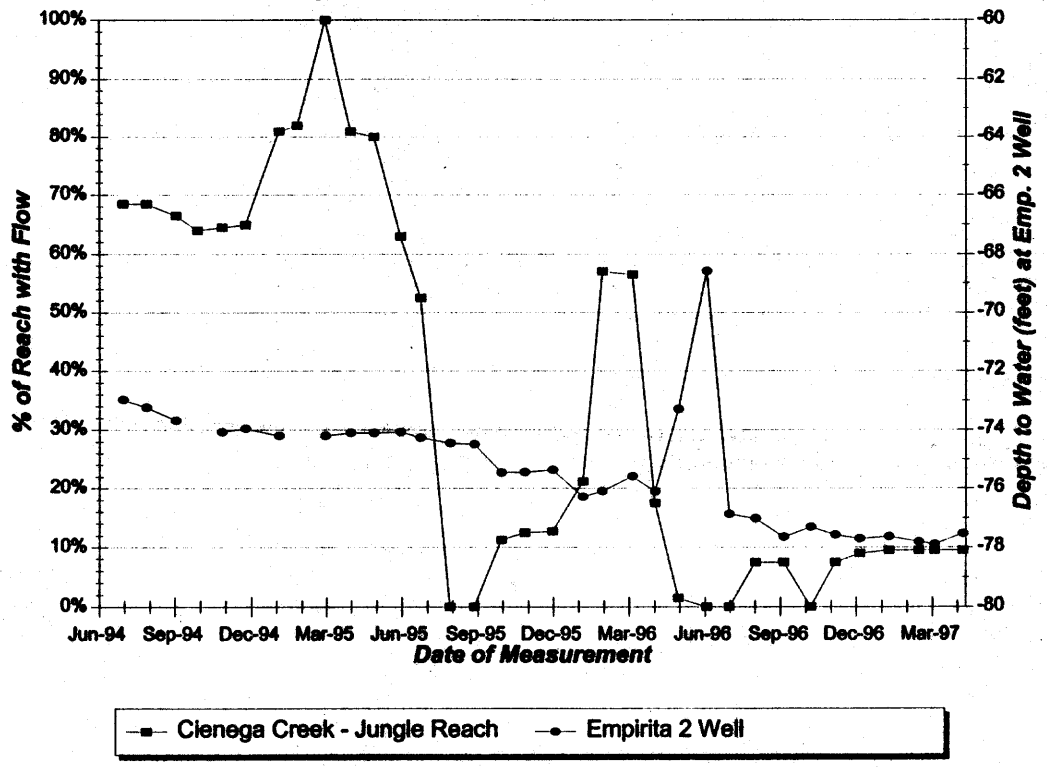

## Figure 44: Groundwater/Surface Water Relationship

Jungle Reach vs. Cienega Well



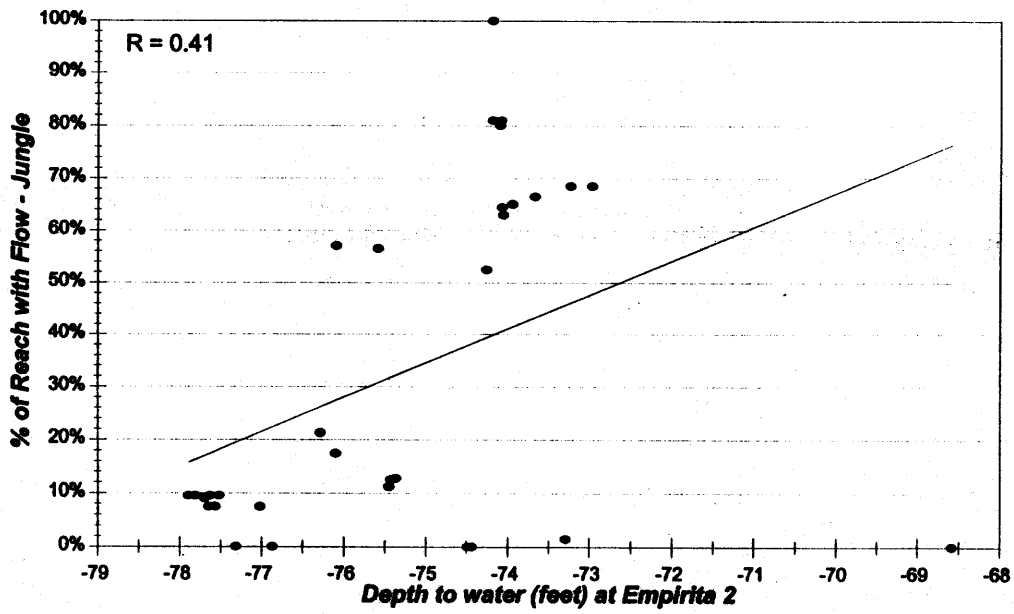
## Figure 45: Groundwater/Surface Water Relationship

Jungle Reach and Empirita 2 Well vs. Time



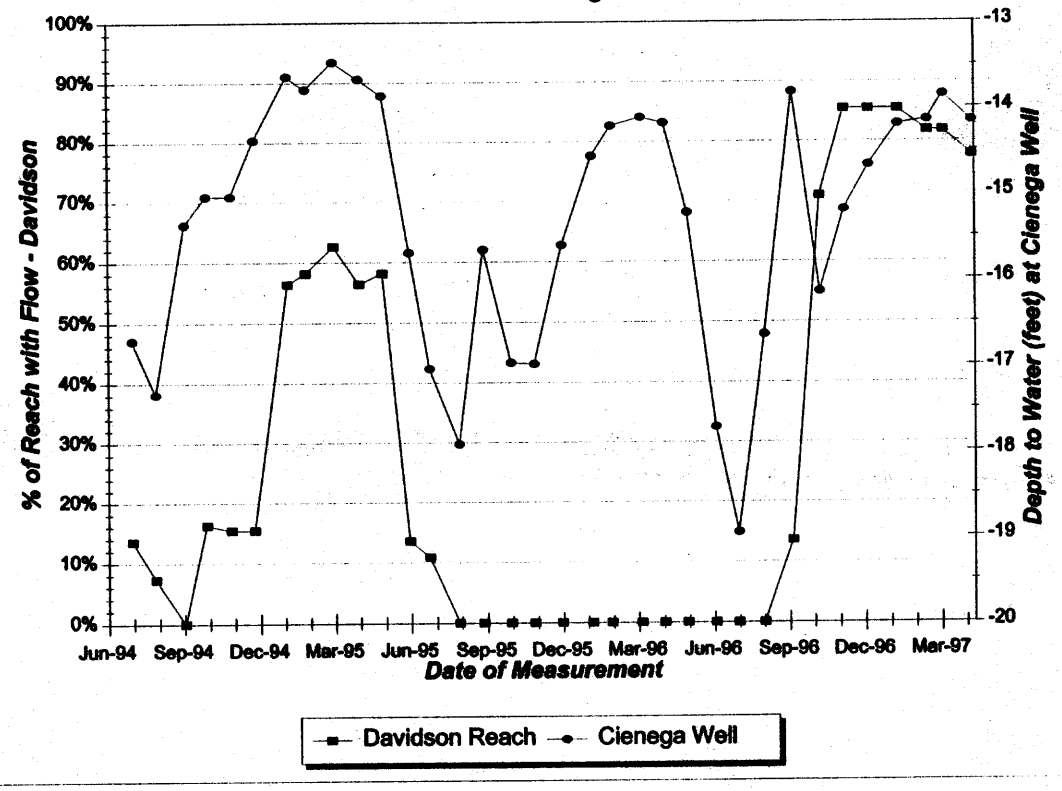

## Figure 46: Groundwater/Surface Water Relationship

Jungle Reach vs. Empirita 2 Well



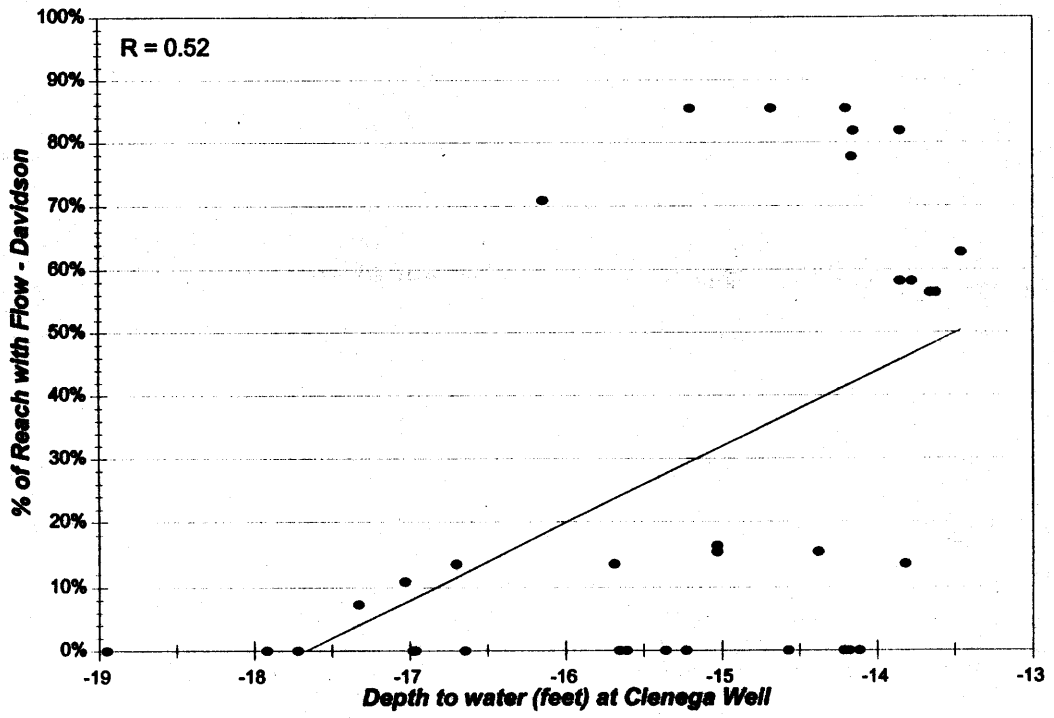
## Figure 47: Groundwater/Surface Water Relationship

Davidson Reach and Cienega Well vs. Time




## Figure 48: Groundwater/Surface Water Relationship

Davidson Reach vs. Cienega Well



Trends in streamflow extent at the Davidson site were also similar, at times, to trends in groundwater levels at the Del Lago #1 well (Figure 49). However, as with the Cienega well, several exceptions were noted, and a linear relationship between streamflow extent at Davidson and groundwater levels at Del Lago #1 was lacking (Figure 50). High-flow conditions were only observed when groundwater depths at the Del Lago #1 well were less than 70 feet bls, but low-flow conditions were observed over the complete range of groundwater levels that were measured. The correlation between the data sets (R = 0.57) was probably limited by the distance between the sites, the effects of the marsh at the Davidson site, and the fact that the Del Lago #1 well was drilled into bedrock.

SP Mile Post 1006 Reach

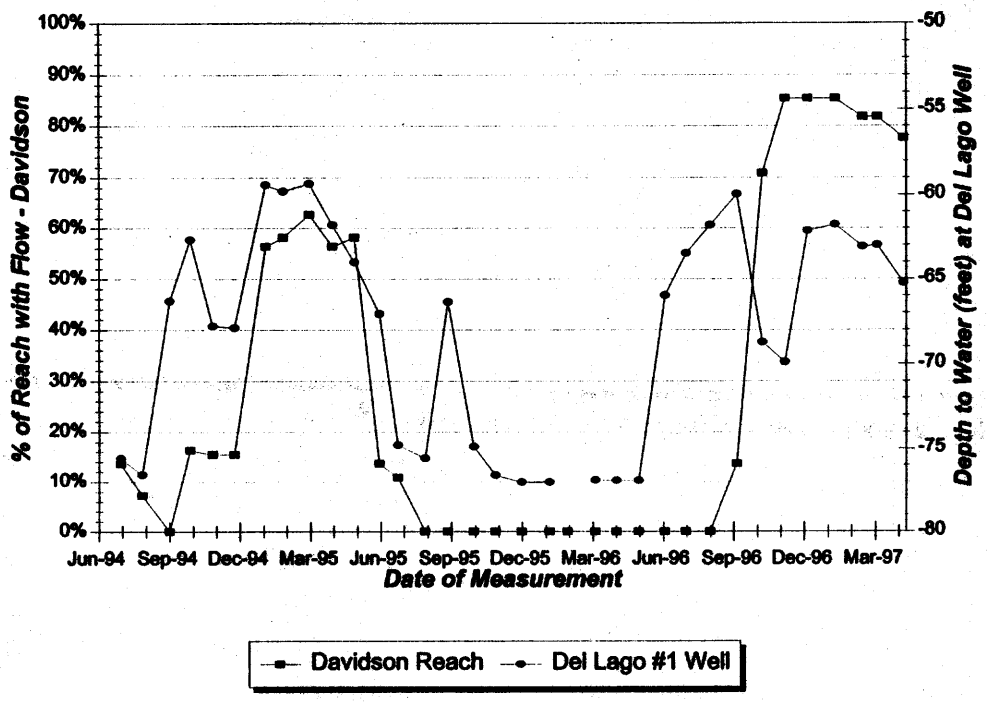
Streamflow extent at the SP 1006 site was compared to groundwater levels at the Cienega well (Figures 51 and 52) and Del Lago #1 well (Figures 53 and 54). Streamflow extent at the SP1006 site was not compared to groundwater levels at the Jungle, Empirita #1 and Empirita #2 wells, because they were upstream from the Cienega well, which was more than five miles upstream from the SP1006 site. Analysis of the data for the Cienega and Del Lago #1 wells, which were the closest actively-monitored wells to the stream reach, was deemed sufficient for evaluating the relationship between flow extent at SP 1006 and water levels along Cienega Creek. The Del Lago #1 well was less than one-half mile downstream from the SP1006 stream reach.

Streamflow extent at the SP 1006 site followed trends similar to trends in groundwater levels at the Cienega and Del Lago #1 wells (Figures 51 and 53). Seasonal increases and decreases in streamflow extent were often concurrent with increases and decreases in groundwater levels. In some cases, however, declines or rises in groundwater levels were not accompanied by decreases or increases in streamflow extent. In some of these instances, the stream reach may have responded via a change in discharge rate, without a change in flow extent. At the SP1006 site, PAG has observed that visually-obvious changes in stream discharge rates have occurred without corresponding changes in flow extent.

As shown by Figures 52 and 54, a strong linear relationship between streamflow extent at SP1006 and groundwater levels at the Cienega and Del Lago #1 wells was not observed. However, continuous flow conditions at SP1006 were only observed when relatively shallow groundwater levels at these wells were measured. Also, the only no-flow observation coincided with the deepest groundwater level recorded at the Cienega well. This observation was made roughly two months after the deepest water levels were recorded at the Del Lago #1 well.

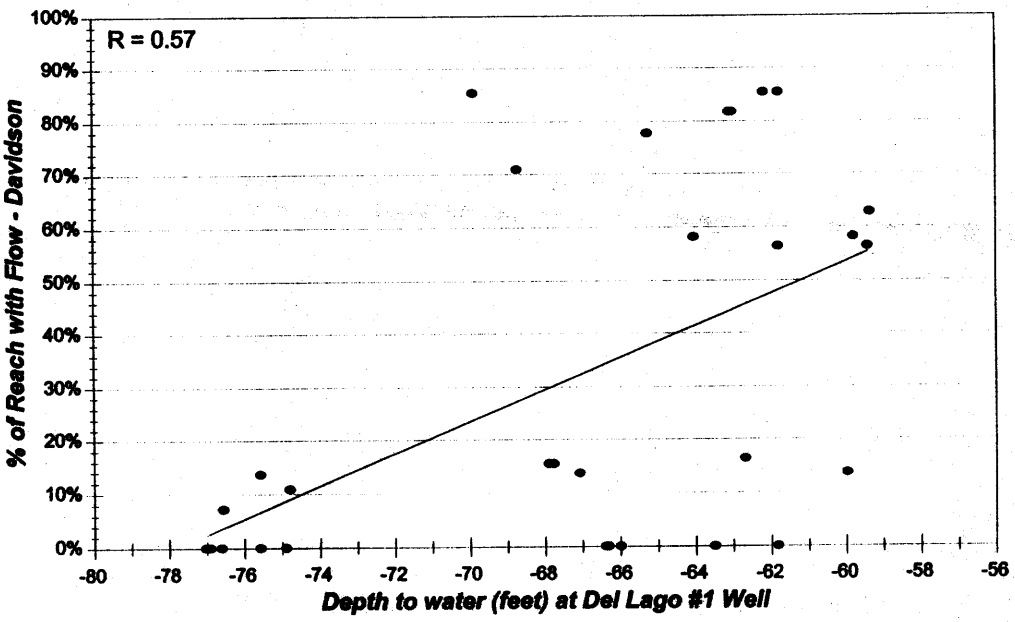
## Figure 49: Groundwater/Surface Water Relationship

### Davidson Reach and Del Lago #1 Well vs. Time



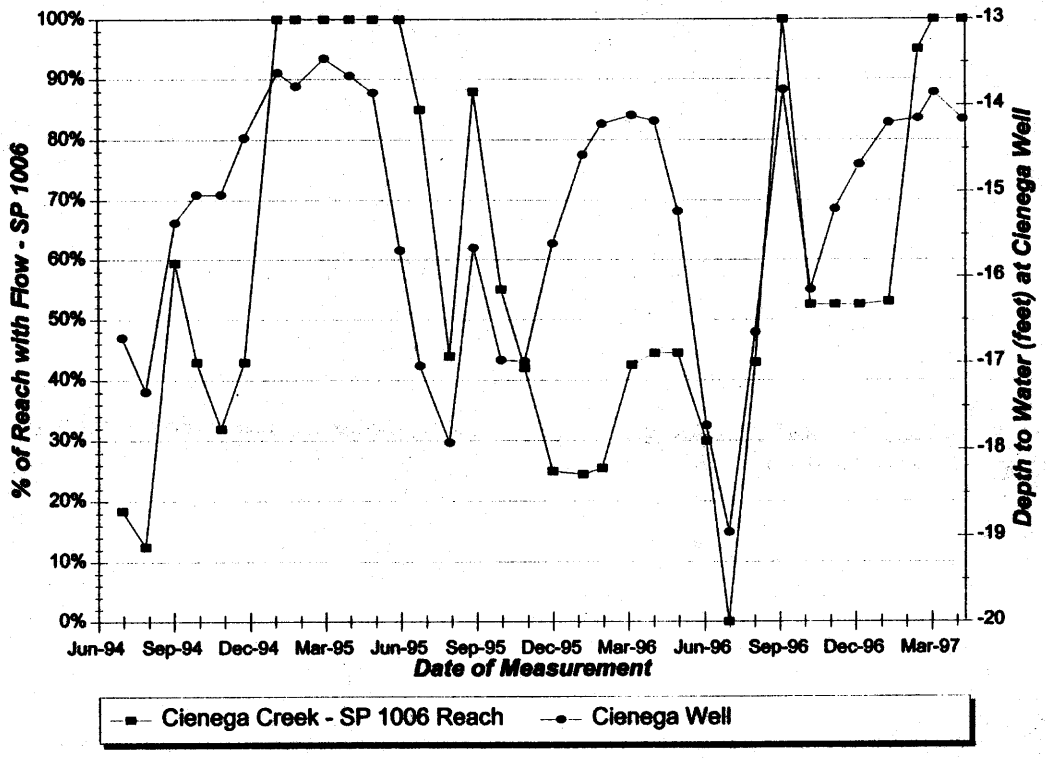

## Figure 50: Groundwater/Surface Water Relationship

### Davidson Reach vs. Del Lago #1 Well



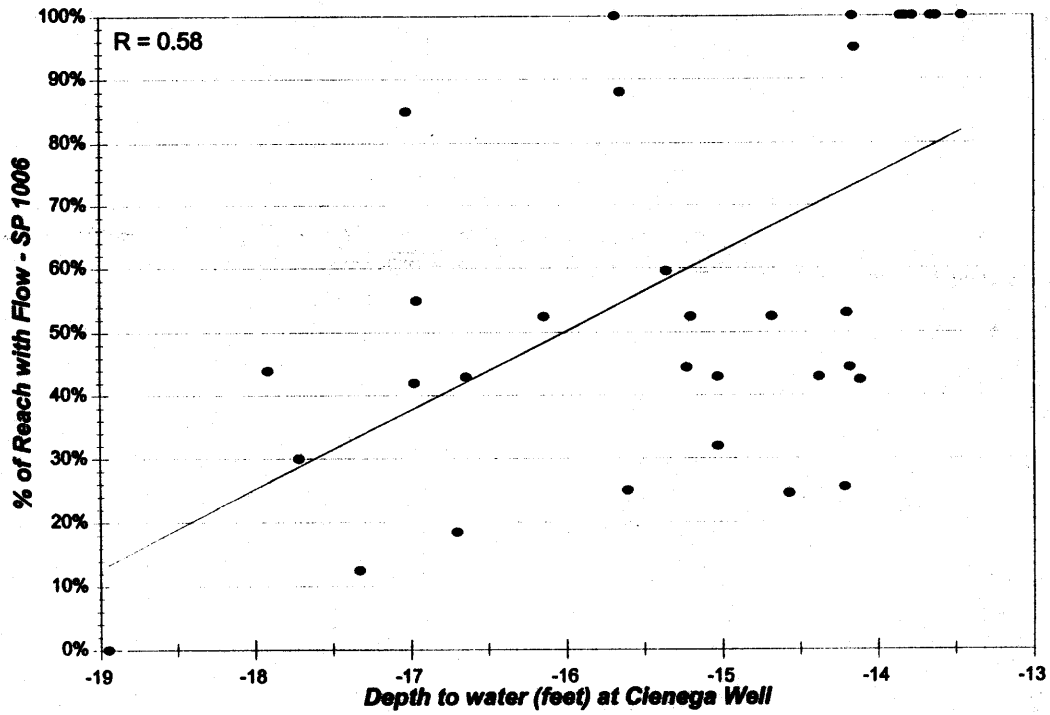
## Figure 51: Groundwater/Surface Water Relationship

SP #1006 Reach and Cienega Well vs. Time



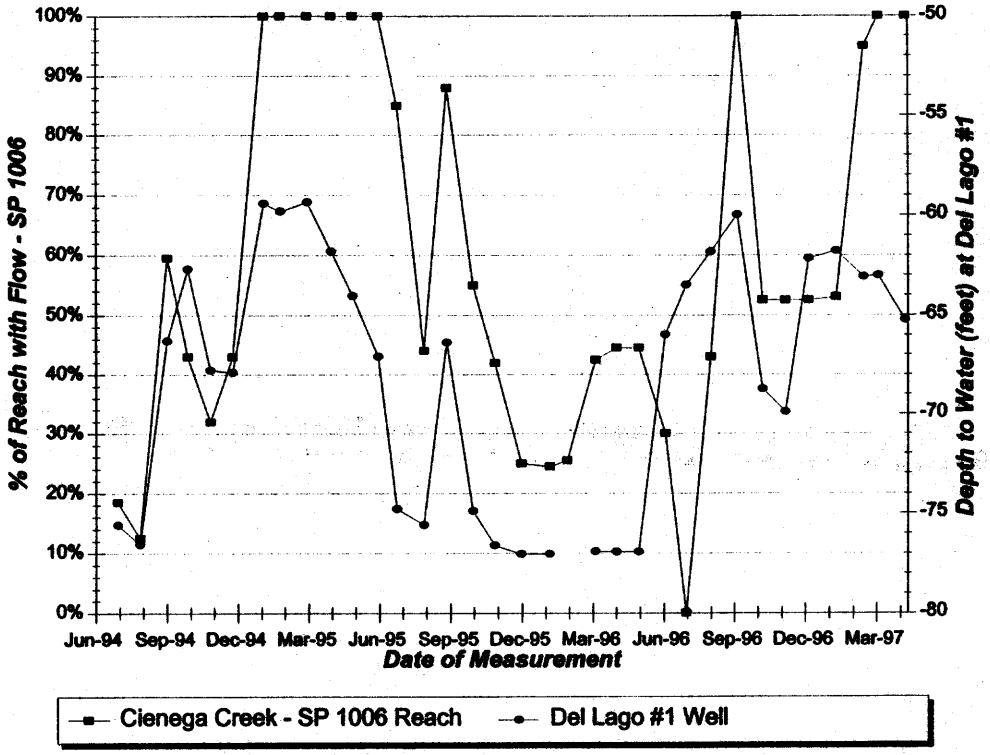

## Figure 52: Groundwater/Surface Water Relationship

SP 1006 vs. Cienega Well



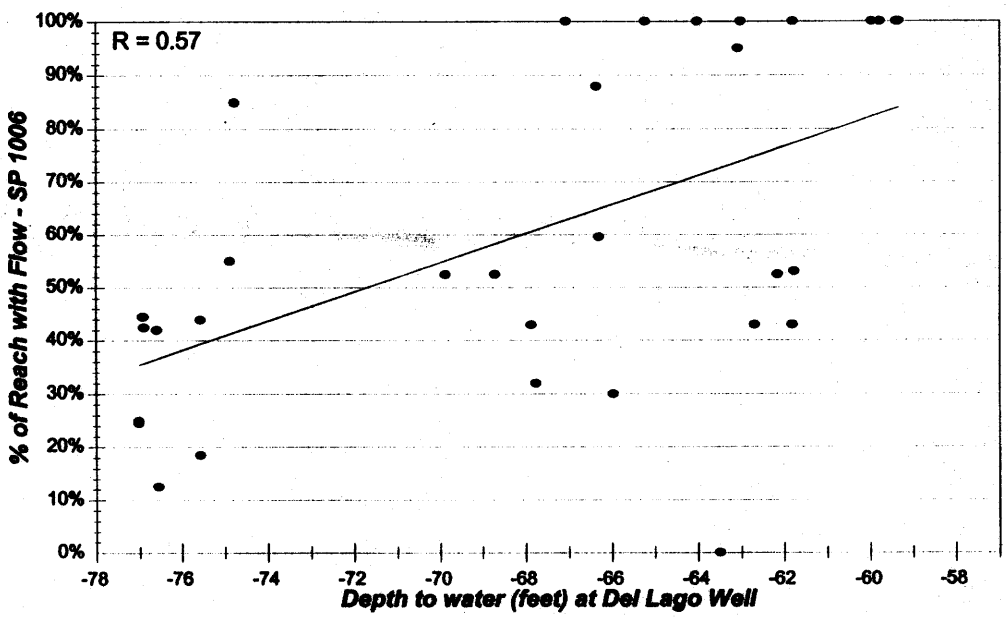
## Figure 53: Groundwater/Surface Water Relationship

SP 1006 Reach and Del Lago #1 Well vs. Time




## Figure 54: Groundwater/Surface Water Relationship

SP 1006 vs. Del Lago #1 Well



Stream Discharge and Groundwater Trends

PAG completed a similar analysis of the relationship between groundwater levels and stream discharge. For each stream-discharge monitoring site, discharge in cubic feet per second (cfs) and depth-to-groundwater in feet at a nearby well were plotted versus time. PAG also created x-y scatter graphs showing stream discharge versus depth to water in a nearby well. The x-y scatter graphs include best-fit lines and correlation coefficients that were calculated by QuattroPro.

Tilted Beds

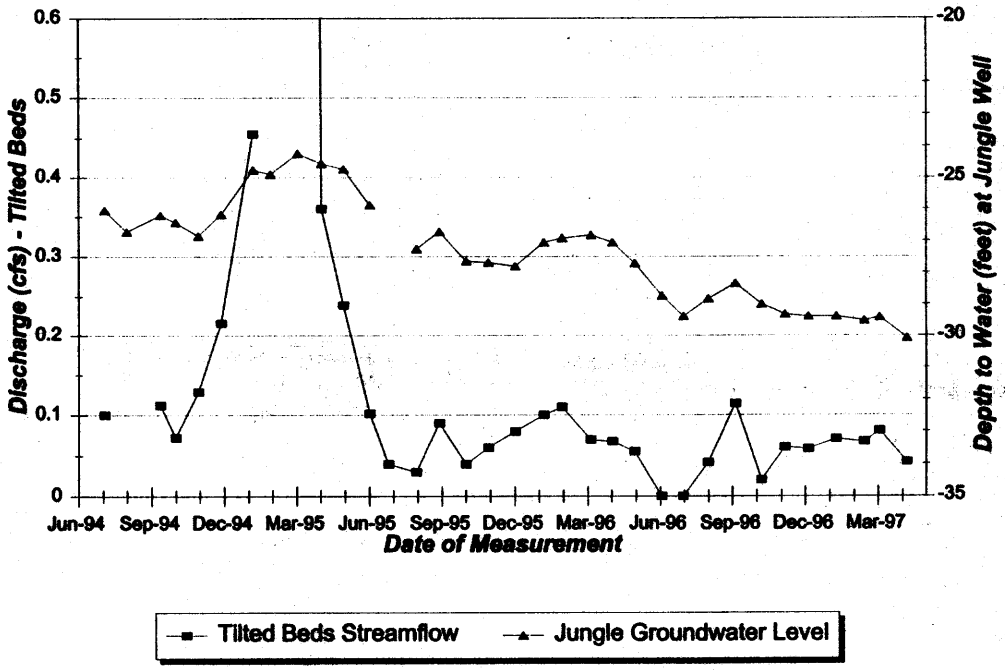
Stream discharge in Cienega Creek at Tilted Beds appeared to be related to groundwater levels at the upstream Jungle and Empirita #1 wells and downstream Cienega well, but not to groundwater levels at the upstream Empirita #2 well and downstream Del Lago #1 well (Table 10). The Tilted Beds site appeared to be most closely correlated with the Jungle well, which was the nearest actively-monitored upgradient well. Seasonal water level trends at the Jungle well occurred simultaneously with seasonal discharge trends at Tilted Beds, and a slight, overall decrease was seen in both data sets (Figure 55). In general, the deepest (and shallowest) groundwater levels coincided with the lowest (and highest) stream discharge. Figure 56 shows a fairly good linear relationship (R = 0.72) between discharge at Tilted Beds and groundwater levels at the Jungle well. This was expected, because groundwater flow rates are directly proportional to hydraulic head (i.e., water level) gradients.

**Table 10. Correlation Between Stream Discharge and Groundwater Levels at Nearby Wells.**

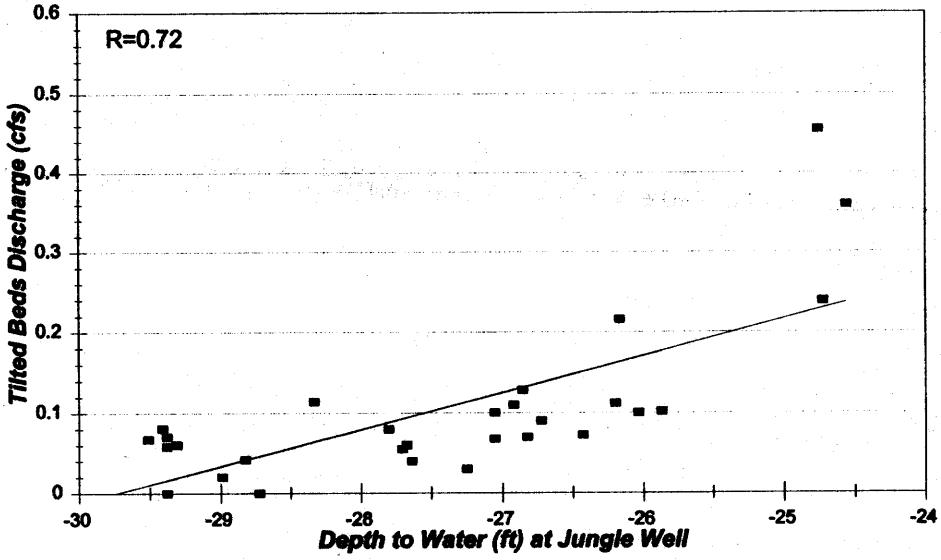
| STREAM LOCATION | WELL | CORRELATION VALUE (R) |
|---|---|---|
| Tilted Beds | Jungle | 0.72 |
| Tilted Beds | Empirita #1 | 0.57 |
| Tilted Beds | Cienega | 0.55 |
| Tilted Beds | Del Lago #1 | 0.36 |
| Tilted Beds | Empirita #2 | 0.19 |
| | | |
| Marsh Station | Cienega | 0.73 |
| Marsh Station | Del Lago #1 | 0.30 |
| Marsh Station | Jungle | 0.29 |
| Marsh Station | Empirita #1 | 0.08 |
| Marsh Station | Empirita #2 | -0.20 |

Trends in stream discharge at Tilted Beds were also fairly similar to trends in groundwater levels at the Empirita #1 well (Figure 57). In general, the highest discharge rates were only recorded when groundwater levels at Empirita #1 were fairly shallow (Figure 58). However, a clear correlation was not observed between the lowest discharge rates and the deepest water levels. Several inconsistent seasonal trends were also noted (Figure 57). For example, minor discharge peaks in September 1995 and September 1996 were not observed in groundwater levels at Empirita #1. Also, discharge increased from 0 cfs in June 1996 to 0.04 cfs in April 1997, while water levels at Empirita #1 dropped by more than one foot. In addition, over the course of the monitoring period, the long-term drop in groundwater levels at Empirita #1 was somewhat sharper than the decline observed in discharge at Tilted Beds. The

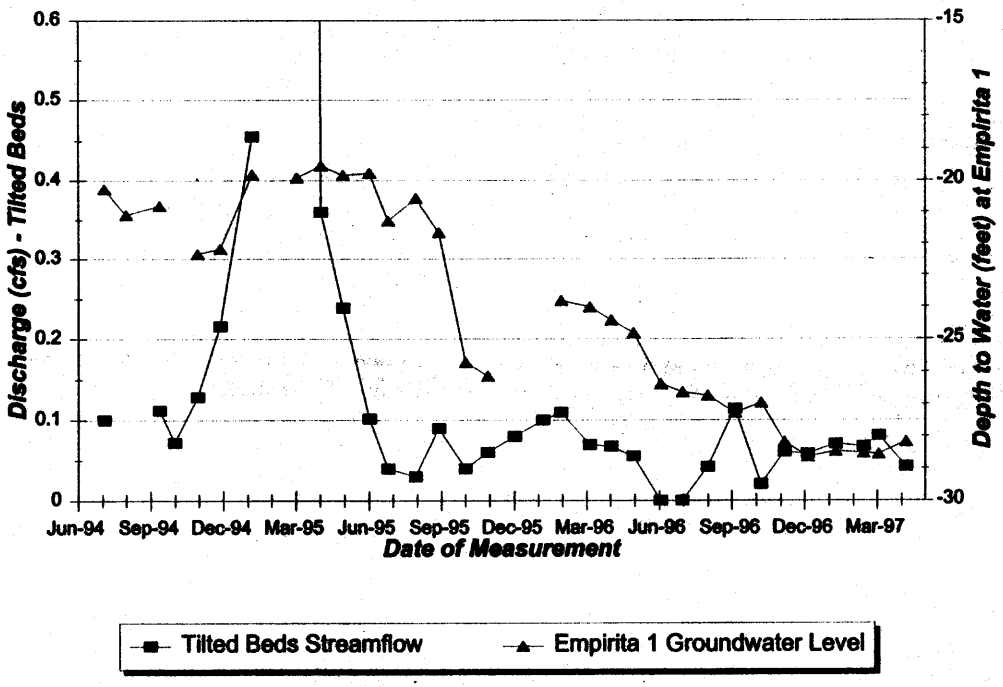
## Figure 55: Discharge at Tilted Beds Site and Depth to Water at Jungle Well vs. Time



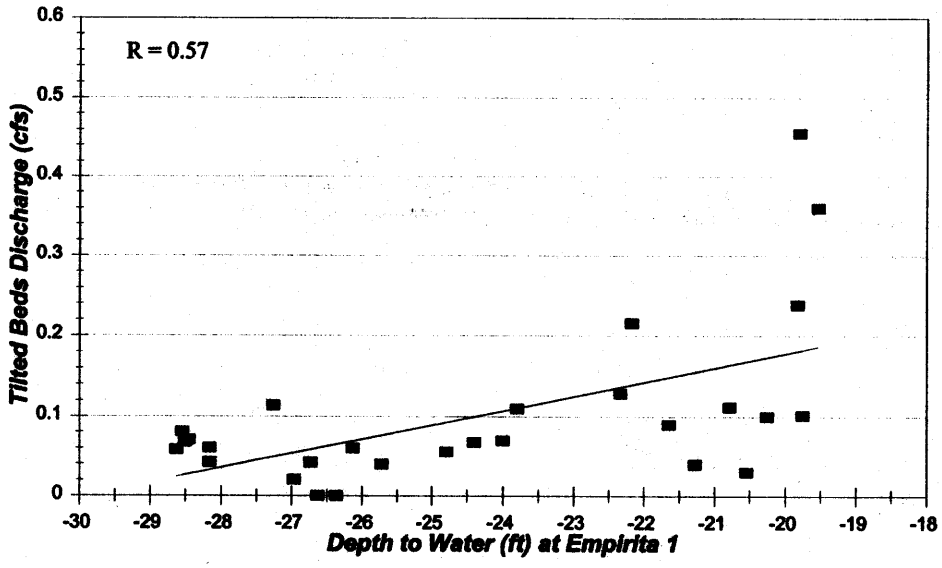

## Figure 56: Discharge at Tilted Beds Site vs. Depth to Water at Jungle Well



## Figure 57: Discharge at Tilted Beds Site and Depth to Water at Empirita #1 Well vs. Time




## Figure 58: Discharge at Tilted Beds Site vs. Depth to Water at Empirita #1 Well



correlation coefficient for the data was 0.57, indicating that the correlation was not as strong as at the Jungle well. The lower correlation was expected, because the Empirita #1 well was farther away. With increasing distance, recharge along tributaries between the sites, regional variations in aquifer transmissivities, and groundwater withdrawals, if any, would be likely to diminish the correlation.

The highest (and lowest) discharge measurements at Tilted Beds coincided with the shallowest (and deepest) groundwater level measurements at the Cienega well, and most seasonal trends were consistent. Some inconsistencies were observed, however. For example, a water level depth of 14.4 ft bls in December 1994 corresponded to a discharge of 0.22 cfs, whereas a water level depth of 14.7 ft bls in December 1996 corresponded to a discharge of only 0.06 cfs. The correlation coefficient for the data was 0.55, which was similar to the correlation coefficient calculated between the Tilted Beds data and the Empirita #1 data. The Empirita #1 well and the Cienega well are roughly the same distance from Tilted Beds.

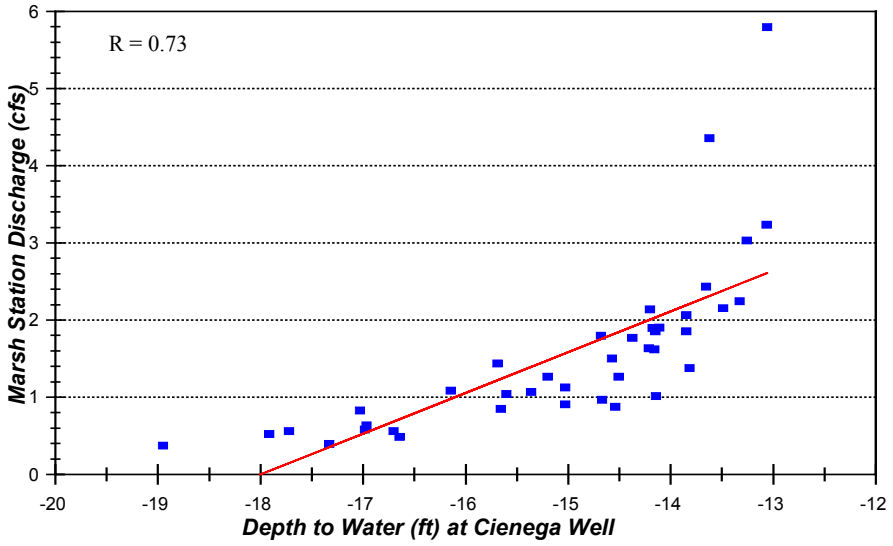
Water levels at the Del Lago #1 and Empirita #2 wells did not appear to be closely correlated with discharge at the Tilted Beds site. The Del Lago #1 well is seven miles downstream from Tilted Beds, and the Empirita #2 well is three miles upstream from Tilted Beds. Neither well taps the younger alluvial aquifer: the Empirita #2 well taps the Pantano Formation and the Del Lago #1 well is drilled into limestone. Seasonal trends at Tilted Beds and Empirita #2 were not consistent, and the correlation coefficient for the data sets was only 0.19. Seasonal trends were somewhat more consistent between Tilted Beds and the Del Lago #1 well, but the magnitudes of increases and decreases were highly variable. The correlation coefficient for these data sets was 0.36. The lack of correlation between Tilted Beds and both of these wells was probably because of the distances to the wells, and because neither well was drilled into the younger alluvial aquifer.

Marsh Station

Stream discharge in Cienega Creek at Marsh Station was closely correlated with groundwater levels at the upstream Cienega well (Figure 59), but not with groundwater levels at other wells along the creek. The Cienega well was the closest actively-monitored well to the Marsh Station site; it was about three miles upstream. Simultaneous seasonal peaks were seen in both data sets during the winter and spring months and in September every year. Simultaneous lows were seen in both data sets every year in early summer. Figure 59 shows that increasing and decreasing flow at Marsh Station was clearly associated with rising and falling water levels at Cienega well. Flows greater than 2 cfs only occurred when groundwater depths at the Cienega well were less than 15 feet bls; flows less than 0.06 cfs only occurred when groundwater levels at the Cienega well were deeper than 16 feet bls. The correlation coefficient for the data was 0.73.

The correlation was less clear at the Del Lago #1 and Jungle wells, which were located about 2.5 miles downstream and 5 miles upstream, respectively. Although these wells showed many seasonal peaks and lows in water level data that were concurrent with peaks and lows in discharge values at the Marsh Station site, the correlation coefficients were only 0.30 for the Del Lago #1 well and 0.29 for the Jungle well. Several seasonal trends at the Del Lago #1 well were inconsistent with trends at Marsh Station. For example, water levels at the well dropped from November 1993 through February 1994, then remained fairly constant through June 1994. In contrast, discharge at Marsh Station rose significantly between November 1993 and March

**Figure 59: Discharge at Marsh Station Site vs. Depth to Water at Cienega Well**




1994, and declined an equal amount between April 1994 and June 1994. Furthermore, water levels at Del Lago #1 remained relatively constant during the winter and spring of 1995-1996 while discharge at Marsh Station increased significantly. Then, between April 1996 and June of 1996, Marsh Station discharge decreased markedly, while Del Lago #1 water levels rose more than 10 feet. Figure 60 shows that a linear relationship between discharge at Marsh Station and groundwater levels at Del Lago #1 was lacking. High and low discharge rates occurred over the entire range of groundwater levels that were measured. The lack of correlation was probably due to the Del Lago #1 well being drilled into bedrock.

Although most of the seasonal trends of increasing or decreasing water levels at the Jungle well were consistent with seasonal trends of increasing or decreasing discharge at Marsh Station, several inconsistencies have been observed (Figure 61). For example, the Jungle well data show a steady, overall lowering of water levels between 1994 and 1997 which is not reflected in the Marsh Station discharge data. In addition, water levels at Jungle remained fairly constant, or dropped slightly, between the fall of 1996 and the spring of 1997. Marsh Station discharge showed a typical seasonal peak during this time. Figure 62 clearly shows that a linear relationship between discharge at Marsh Station and groundwater levels at the Jungle well was lacking. High and low discharge rates occurred over the entire range of groundwater levels that were measured. Effects of the bedrock high at Tilted Beds, and possibly Tilted Beds spring, both of which are located between the Cienega and Jungle wells, might explain why Marsh Station's correlation with Jungle well was so much poorer than the correlation with Cienega well.

No correlation was found between discharge at Marsh Station and water levels at the Empirita #1 and Empirita #2 wells (Table 10). The factors limiting the correlation between

**Figure 60: Discharge at Marsh Station Site vs. Depth to Water at Del Lago #1 Well**

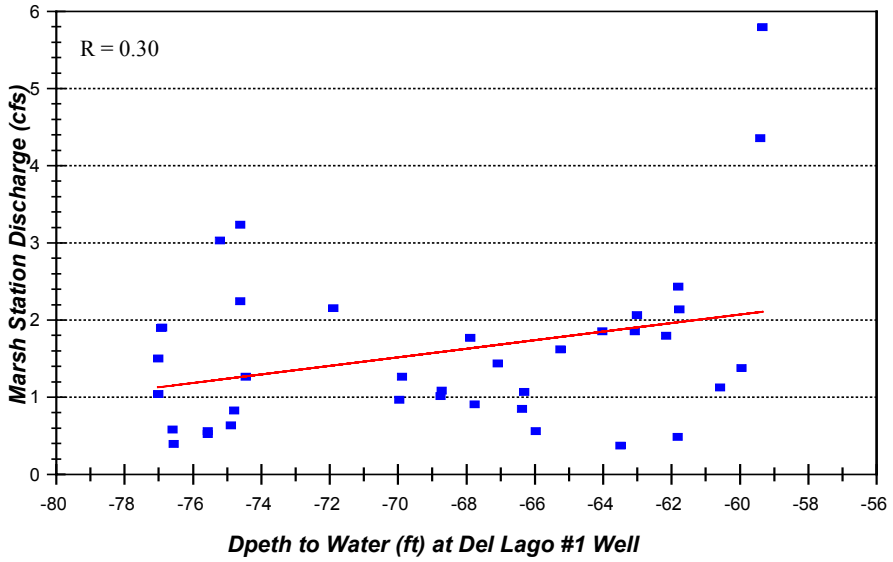



**Figure 61: Discharge at Marsh Station Site and Depth to Water at Jungle Well vs. Time**

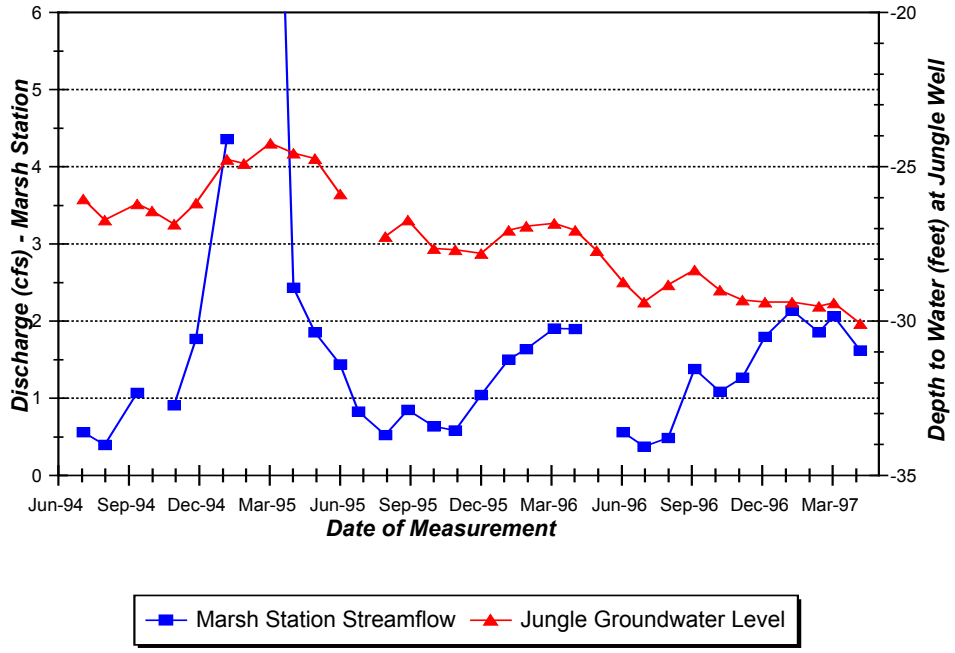
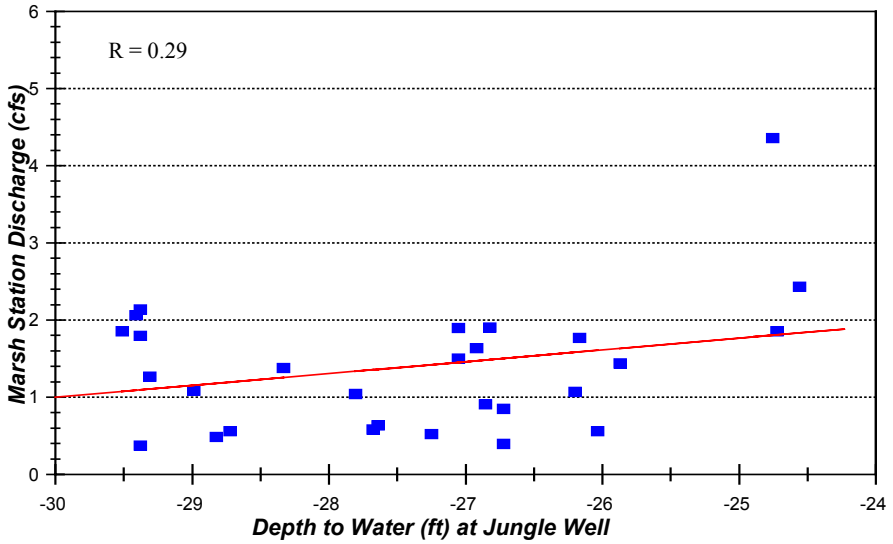


**Figure 62: Discharge at Marsh Station Site vs. Depth to Water at Jungle Well**




Marsh Station discharge and Jungle well water levels would also apply to these wells, because they are even farther upstream from Marsh Station than the Jungle well. In addition, the Empirita #2 well is perforated in the Pantano formation, not in the shallow alluvial deposits.

Summary

Streamflow in Cienega Creek was closely related to conditions in the local aquifer. This interpretation was based on numerous observations that streamflow rates (discharge) and streamflow extent were correlated with water level trends in nearby wells. However, the correlation diminished substantially with increasing distance between the stream reach and the groundwater monitoring location, particularly if significant bedrock highs were present between the locations. Streamflow extent and discharge appeared to be better correlated with groundwater levels in wells drilled in the younger alluvial deposits than with water levels in wells drilled in either the Pantano formation or bedrock. These interpretations, however, were based on a fairly limited time period, and only on an analysis of concurrent data. The analysis did not address whether a delayed correlation (i.e., a time lag) might exist between streamflow trends and groundwater levels in wells located farther away and/or drilled into the Pantano formation or bedrock. Data representing a longer period of time would be needed for such an analysis.

# VII. DIURNAL VARIATIONS IN STREAM DISCHARGE AND GROUNDWATER LEVELS, AND ESTIMATES OF EVAPOTRANSPIRATION RATES

PAG conducted measurements of the diurnal variations in Cienega Creek streamflow and groundwater levels on five days between 1995 and 1997. The dates and locations of the measurements are presented on Table 11; locations are shown on Figure 63. The original purpose of the diurnal measurements was to determine whether conducting the monthly discharge and groundwater level measurements at different times of day would introduce sufficient error to obscure seasonal or long-term trends. The data were also compared to hourly meteorological data to evaluate the effects of evapotranspiration (ET) on groundwater levels and stream discharge, and to evaluate the effects of barometric pressure on groundwater levels.

One of the goals of this study was to use the diurnal data to estimate a water budget for Cienega Creek. PAG reviewed a variety of data and several publications to evaluate the feasibility of this goal. Based on this effort, it was determined that a valid water budget could not be developed within the time and budget available for this project, because of numerous uncertainties and data gaps. However, the data reported in this document should be useful in any future attempt to develop a water budget for Cienega Creek.

**Table 11. Diurnal Discharge and Groundwater Level Measurements**

| Date | Groundwater Location | Stream Discharge Location |
|---|---|---|
| | | |
| 6/22/95 | Del Lago #1 Well | Del Lago Dam |
| 1/12/96 | Del Lago #1 Well | Del Lago Dam |
| 6/18/96 | Del Lago #1 Well | Del Lago Dam |
| 6/23/96 | Cienega Well | Marsh Station Bridge |
| 3/18/97 | Cienega Well | Marsh Station Bridge |

Diurnal Meteorological Data

For each of the diurnal measurement dates, PAG collected meteorological data from the Western Regional Climate Center (WRCC) for a station located at the Tucson International Airport. This was the closest weather station that could provide all of the necessary data. WRCC data included hourly measurements of temperature, barometric pressure, wind speed, relative humidity, precipitation, and dew point. These data, with the possible exception of wind speed, were probably representative of the lower Cienega Creek basin. No rainfall occurred on any of the diurnal measurement dates.

Figures 64 through 68 show temperature and barometric pressure for each of the diurnal measurement dates. Each of these graphs showed a cyclical variation in barometric pressure that generally corresponded to the daily temperature trends. Pressure

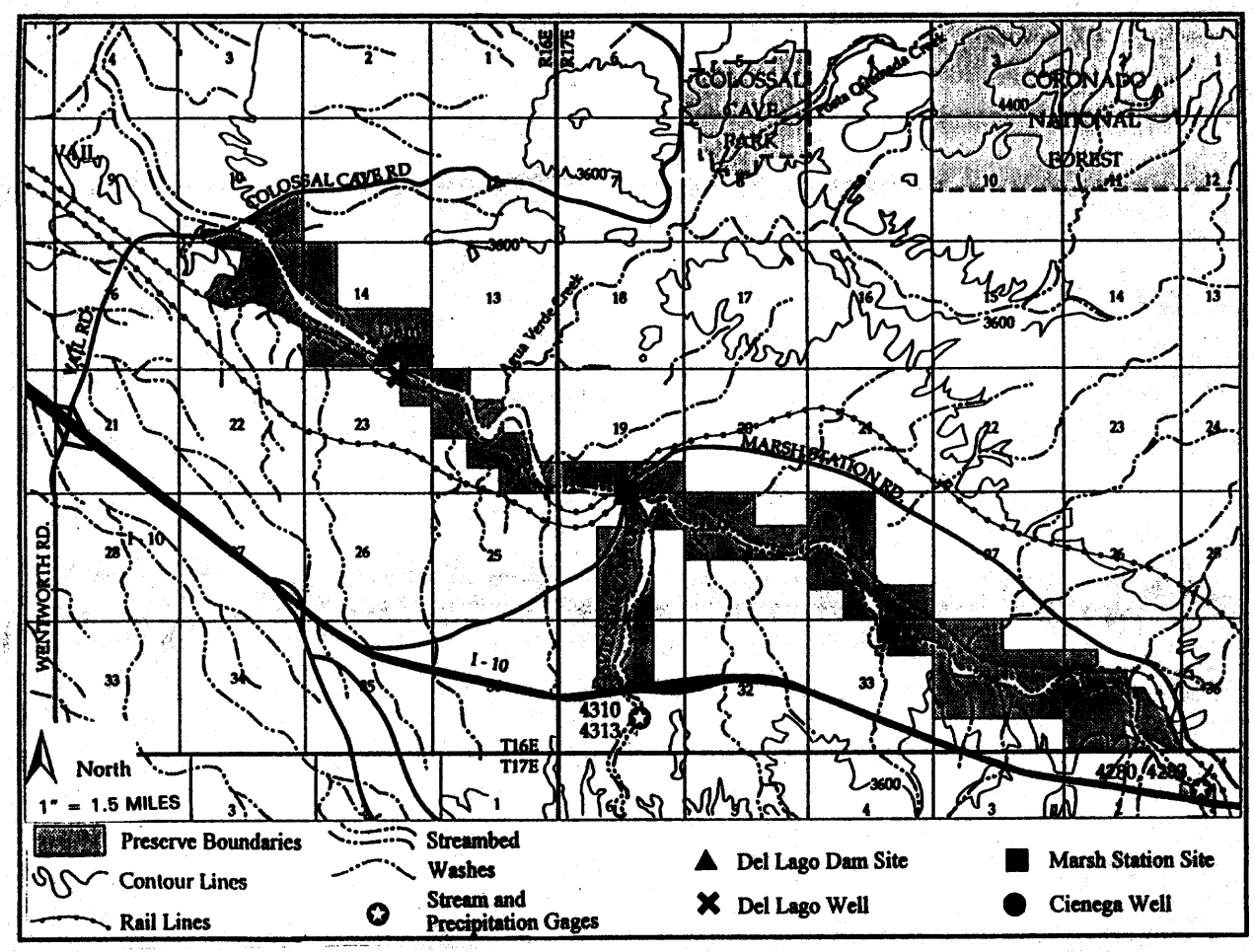
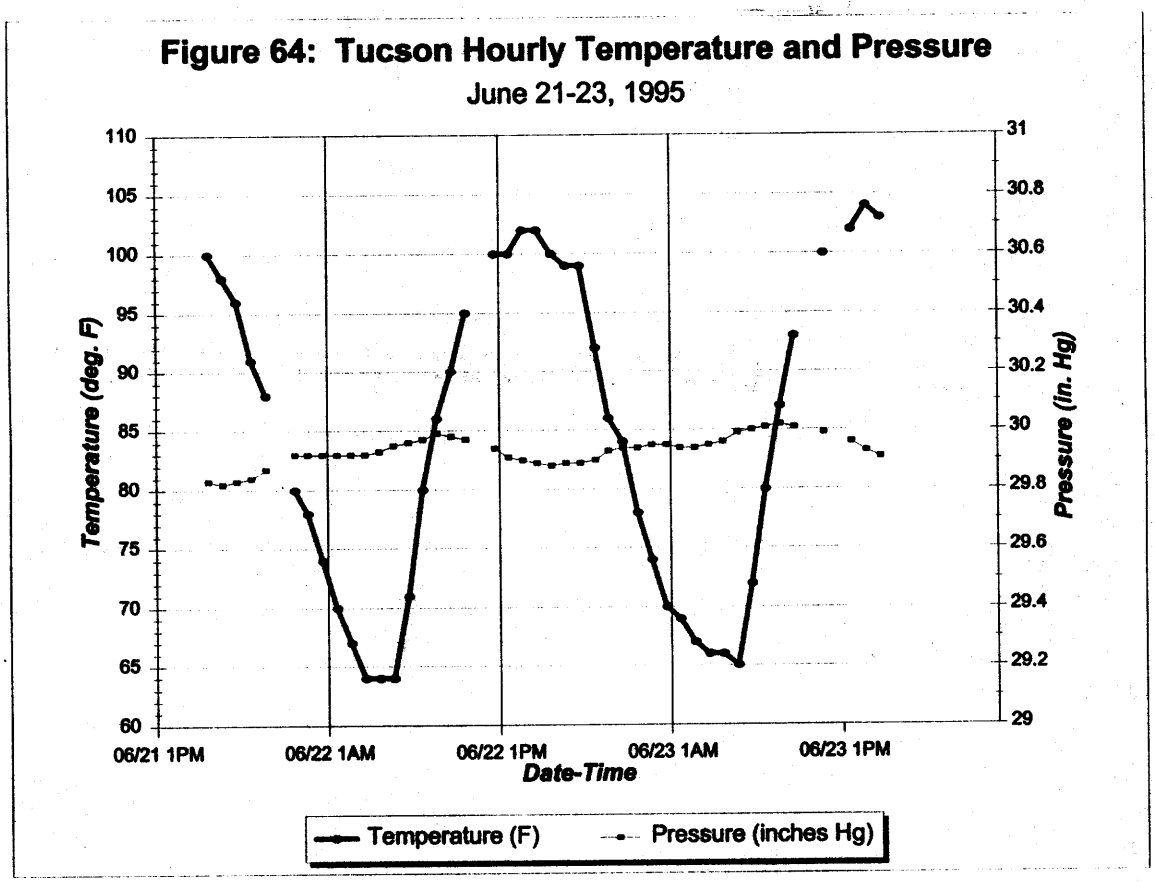


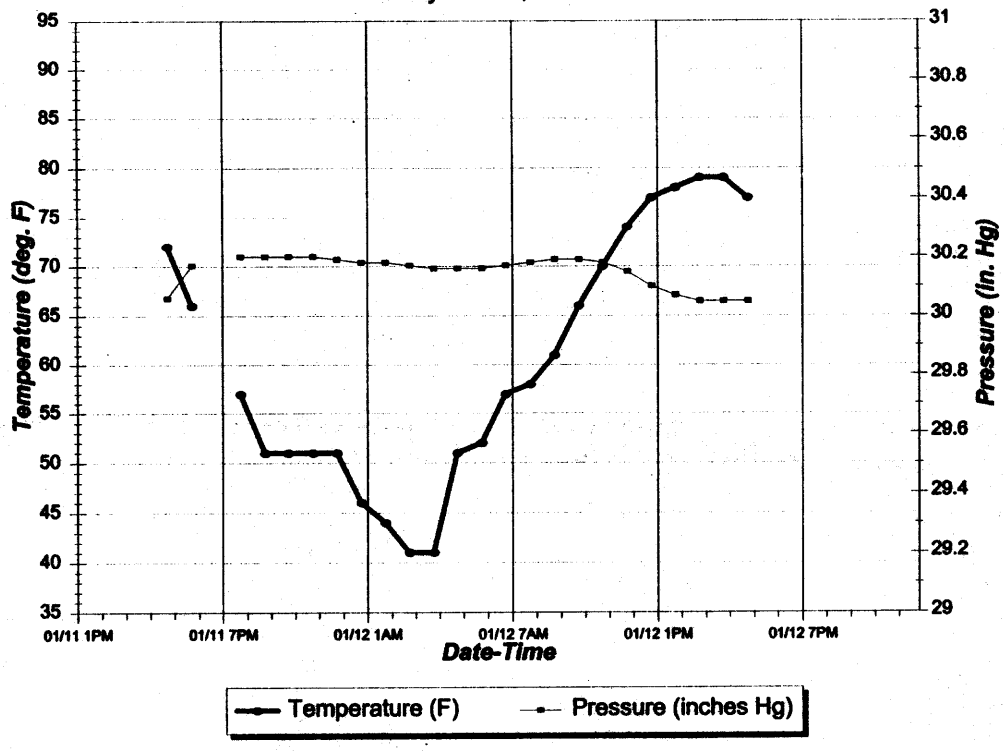

**Figure 63: Locations of PAG's Diurnal Flow and Groundwater Level Measurements**

* Note: Base map provided to PAG by Pima County Flood Control District



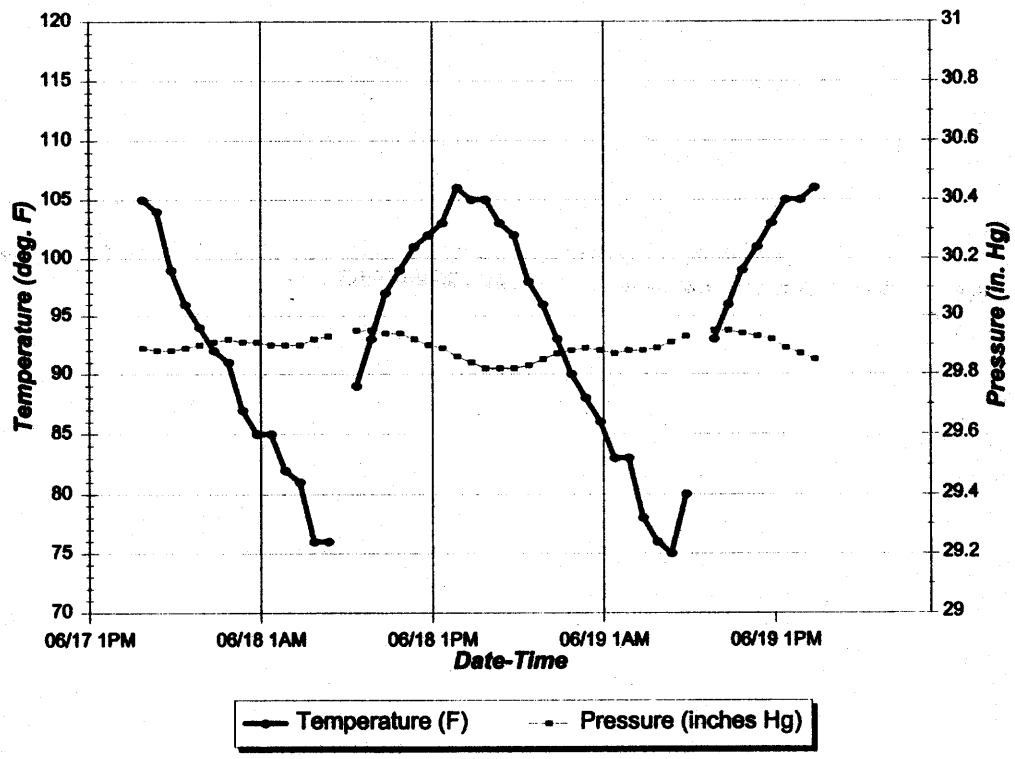
## Figure 65: Tucson Hourly Temperature and Pressure

January 11-12, 1996



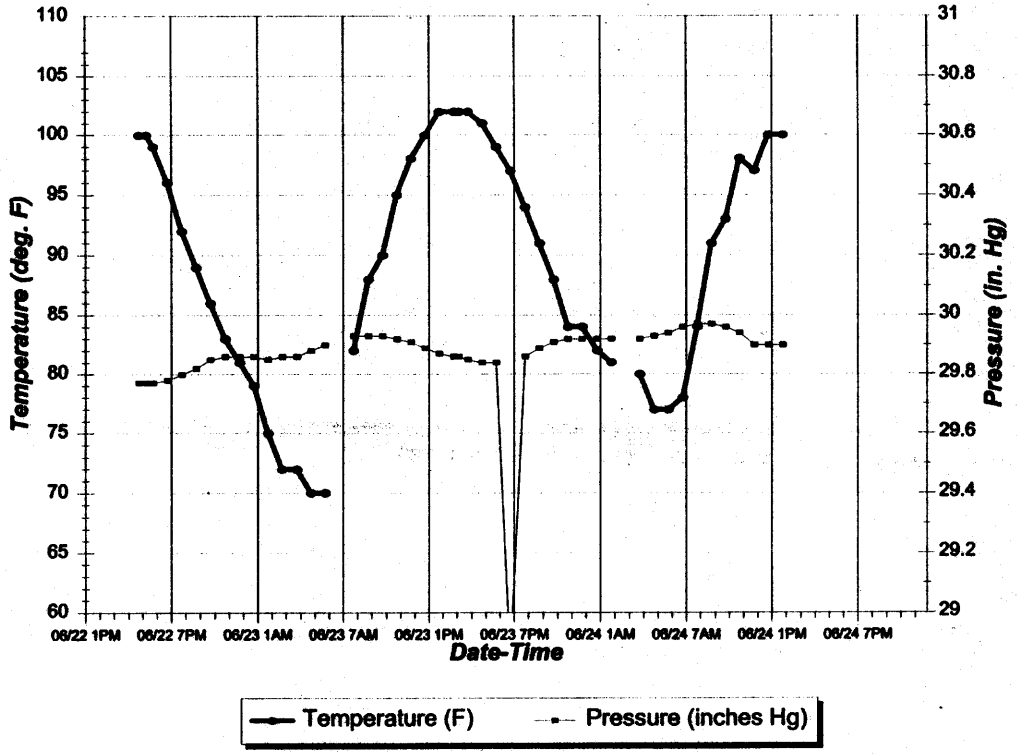

## Figure 66: Tucson Hourly Temperature and Pressure

June 17-19, 1996



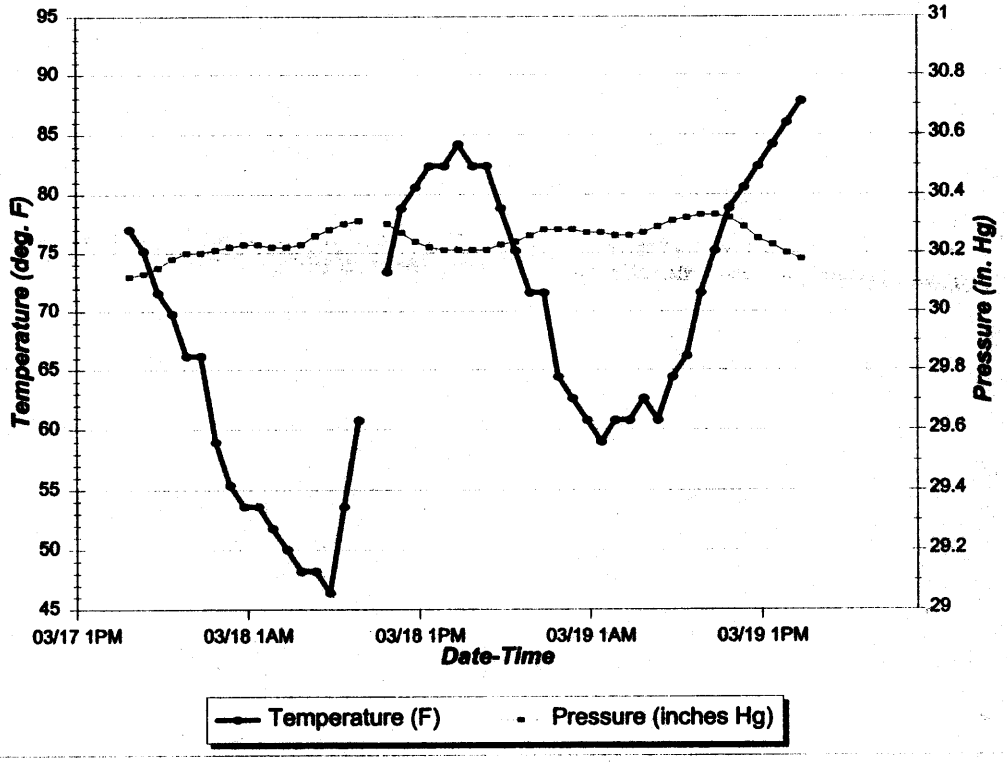
## Figure 67: Tucson Hourly Temperature and Pressure

June 22-24, 1996




## Figure 68: Tucson Hourly Temperature and Pressure

March 17-19, 1997



lows were generally associated with temperature highs. High pressures generally occurred early in the morning or late in the evening.

Evapotranspiration rates are strongly affected by temperature, wind speed and relative humidity. Data for these conditions were reviewed for the days on which the diurnal measurements were made. The relative humidity was generally lowest during the heat of the day and highest during the cooler nights. Both temperature and relative humidity changed gradually over the course of the day. In contrast, the wind speed fluctuated dramatically throughout the day, suggesting that somewhat gusty conditions prevailed on these dates. Wind speeds were generally higher during the day than at night, probably due to thermally driven convection currents in the air. Increased wind speeds during the hot part of the day were apparent on all of the diurnal measurement days except for March 18, 1997, which showed no significant increase in wind speed during the day.

Diurnal Groundwater Measurements

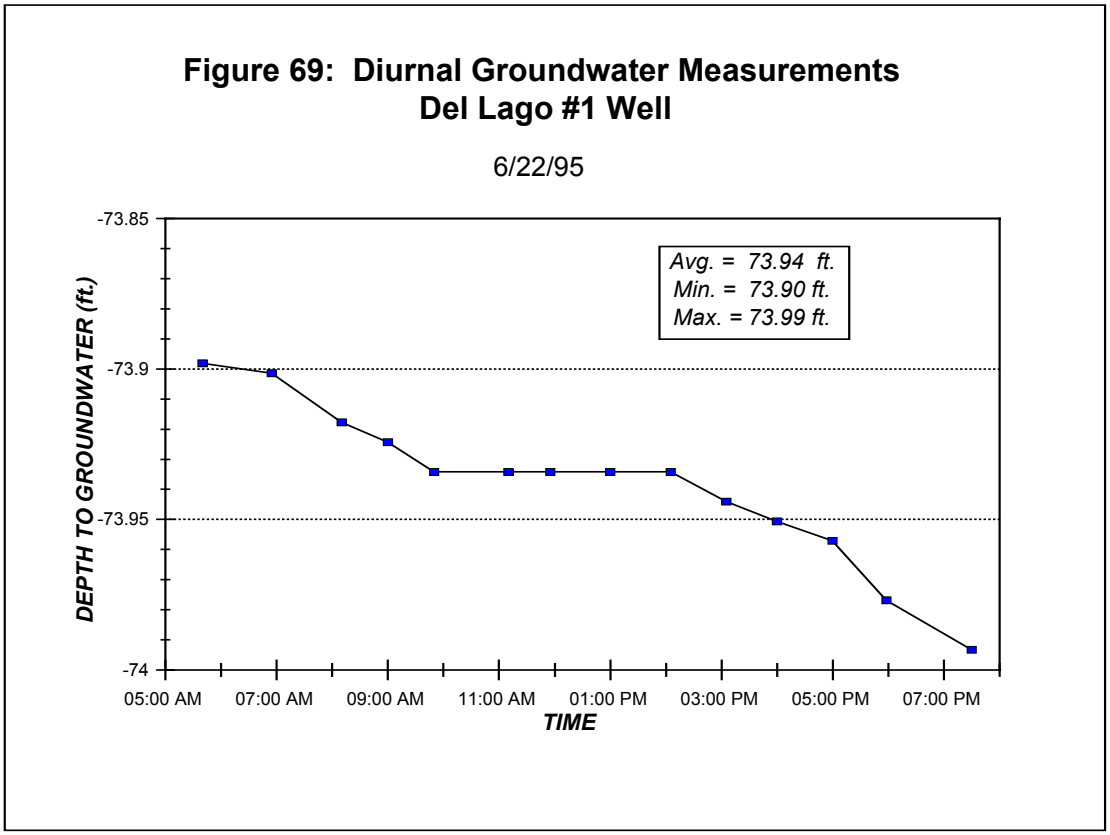
PAG conducted five diurnal groundwater measurements at two well locations, Del Lago #1 and Cienega, to determine if the effects of evapotranspiration could be detected in the water table. The electric sounder used for the monthly groundwater measurements was also used during the diurnal groundwater measurements, with consistent methodology applied during all measurements. The results of the diurnal groundwater measurements are summarized on Table 12. Hourly variations in groundwater levels are illustrated for each of the measurement dates on Figures 69 through 73.

**Table 12. Diurnal Groundwater Measurement Results**

| Well | Date | NET WL CHANGE (feet) | AVG. DTW (feet) | MIN. DTW (feet) | Time | MAX. DTW (feet) | Time |
|---|---|---|---|---|---|---|---|
| **Del Lago 1** | 6/22/95 | 0.09 | 73.94 | 73.90 | 5:40a | 73.99 | 7:30p |
| **Del Lago 1** | 1/12/96 | 0.04 | 77.03 | 77.01 | 1:30p | 77.05 | 7:27a |
| **Del Lago 1** | 6/18/96 | 0.08 | 63.85 | 63.81 | 5:00p | 63.89 | 5:25a |
| **Cienega** | 6/23/96 | 0.28 | 18.69 | 18.56 | 7:36a | 18.84 | 1:07p |
| **Cienega** | 3/18/97 | 0.07 | 14.08 | 14.05 | 12:10p | 14.12 | 8:36a |

WL = water level
DTW = depth to water in feet below land surface

The first diurnal groundwater measurement was completed on June 22, 1995 at the Del Lago #1 well (Figure 69). The measurement was taken on a clear, hot 100$^{o}$ F+ day, when evapotranspiration rates should be among the highest of the year. No significant variation was found in the groundwater level, which ranged from 73.90 ft BLS at 6:00 AM to 73.99 ft BLS at 7:30 PM. A slight deepening trend in the groundwater was observed throughout the day. This trend apparently was not due to ET, because the water level was stable between 10:00 AM and 2:00 PM, when ET was probably at a maximum. It was also not due to fluctuations in barometric pressure, which dropped steadily during the day. Instead, the trend was most likely part of a longer-term, seasonal decline that is apparent on Figure 12 (Section IV).




On January 12, 1996, PAG conducted a second diurnal groundwater measurement at the Del Lago #1 well (Figure 70). The weather on this day was warm (70$^{o}$F+), and dry conditions prevailed. Again, there were no significant diurnal variations found in the groundwater level. The minimum depth of 77.01 ft (BLS) was recorded at 1:30 P.M. and the maximum depth of 77.05 ft. (BLS) was recorded at 7:27 A.M. The slight water level rise recorded between 11:00 AM and 2:00 PM might have been due to a drop in barometric pressure recorded during the same time period (Figure 65).

On June 18, 1996, PAG staff conducted a third diurnal groundwater level measurement at the Del Lago #1 well (Figure 71). The weather was clear and 105$^{o}$F+, with no wind. No precipitation had been recorded for several months prior to this measurement. Once again, no significant diurnal variation was found. The difference between the maximum and minimum depths was only 0.08 ft. The deepest reading of 63.89 ft. (BLS) was recorded at 5:30 A.M., while the most shallow groundwater level of 63.81 ft. (BLS) was measured at 5:00 P.M. The steady rise in water levels recorded during this diurnal measurement was opposite to the trend that was observed in June 1995, and was not consistent with expected diurnal variations influenced by high ET rates characteristic of this time of year. The rise was not a result of a recent flood event, because no flood flows were recorded at the USGS gaging station at the Del Lago dam during the three months preceding the diurnal measurement (USGS, 1996). The water level rise might have been due to falling barometric pressure (Figure 66), or it might have been part of the longer-term, anomalous seasonal rise recorded at this well between May 1996 and September 1996 (Figure 12).

**Figure 70: Diurnal Groundwater Measurements**
**Del Lago #1 Well**

1/12/96

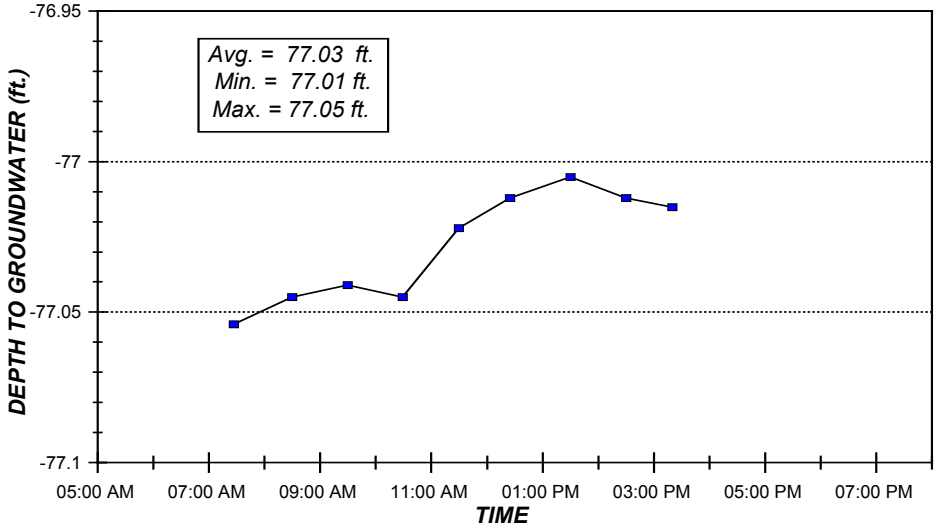
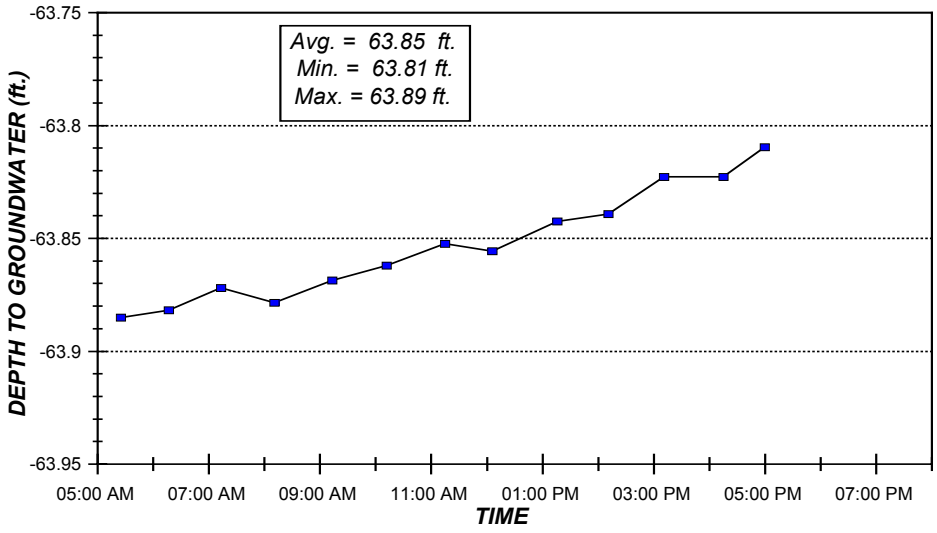



**Figure 71: Diurnal Groundwater Measurements**
**Del Lago #1 Well**

6/18/96



The three diurnal measurements conducted at the Del Lago #1 well indicated that groundwater levels at this well were not strongly affected by diurnal variations in the evapotranspiration rate. This was probably because the well terminated at a depth of 308 ft. (BLS) in bedrock. The maximum reported rooting depth for Fremont cottonwoods and Goodding willows is 7 feet (Zimmerman, 1969), which suggests that ET would only have a significant effect on the shallow alluvial aquifer.

A diurnal groundwater measurement was conducted on June 23, 1996 at the Cienega well (Figure 72). Evapotranspiration effects on groundwater levels were likely to be more significant at this well than at the Del Lago #1 well, because the Cienega well is 80 feet deep, it is drilled into alluvium, and it is surrounded by mature mesquite trees. The weather on this day was sunny, 100$^{o}$F+, with a slight breeze. No precipitation had been recorded for several months prior to this measurement. A clear diurnal trend in groundwater levels was observed. The groundwater level was shallowest at 7:36 A.M., with a reading of 18.56 ft. (BLS). The groundwater level dropped steadily until about 1:00 PM. From 1:00 to 3:00 P.M., the water level stabilized at its deepest level of 18.84 ft. (BLS). From 3:00 to 5:00 P.M., the water level rebounded considerably to 18.58 ft. (BLS).

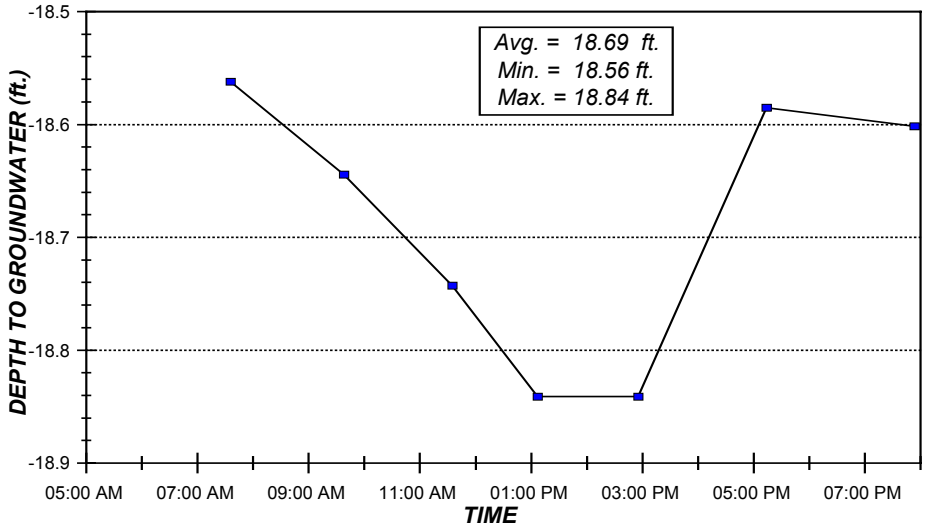
The water level trends were probably due to variations in evapotranspiration. The shallowest water level was recorded when temperature and wind speed were low and relative humidity was high; the deepest water levels were recorded when temperatures and wind speed were high and relative humidity was low. The trend did not appear to be due to fluctuations in barometric pressure, which declined steadily while the water level dropped (Figure 67).

A second diurnal groundwater measurement was conducted at the Cienega well on March 18, 1997, when the ET rate was expected to be at a moderate level (Figure 73). All other previous diurnal groundwater measurements at either the Del Lago #1 or Cienega well had been made when evapotranspiration was near a maximum or minimum rate. For this measurement, conditions were seasonally characteristic, with the high temperature in the mid-80's, and slight breezes increasing from morning to afternoon. The maximum depth to groundwater of 14.12 ft. (BLS) was recorded for a period between 8:00-10:00 am, while the most shallow measurement of 14.05 ft. (BLS) was measured between 12:00-1:00 P.M. No discernible hourly trend was found, suggesting that evapotranspiration had minimal effects on groundwater levels during this time of year.

In summary, diurnal variations in water levels at the Del Lago #1 and Cienega wells appeared to be relatively minor. Seasonal and long-term trends should be apparent regardless of the time of day that monthly measurements are taken. However, it appears that the Cienega well, with a total depth of 80 ft. and penetrating the alluvial and basin fill aquifers, is more responsive to variations in the ET rate than the Del Lago #1 well, which has a total depth of 308 feet and is drilled into bedrock. Therefore, summer-season measurements at the Cienega well should be taken at roughly the same time of day.

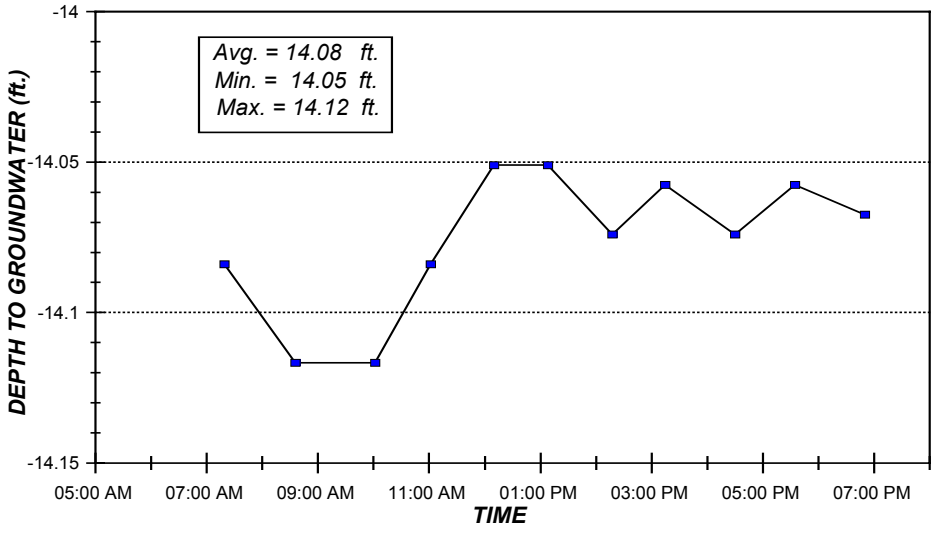
## Figure 72: Diurnal Groundwater Measurements
## Cienega Well

6/23/96




## Figure 73: Diurnal Groundwater Measurements
## Clenega Well

3/18/97



Diurnal Flow Measurements

In order to evaluate diurnal variations in Cienega Creek discharge, PAG conducted five diurnal flow measurements between 1995 and 1997. The measurements were conducted three times in the summer, once in the winter, and once in the spring. For each of the diurnal discharge measurements, PAG measured instantaneous stream discharge roughly every hour throughout the day. PAG used the same methodology for the hourly instantaneous measurements that was used for the monthly instantaneous measurements at Marsh Station Bridge. The same Qualimetrics brand, Model 6660 digital water current meter was used, and the instantaneous discharge was calculated from velocity and depth measurements made at equally-spaced intervals across the stream channel.

Table 13 summarizes the results of the diurnal flow measurements. Hourly variations in discharge are illustrated for each of the measurements on Figures 74 through 78.

**Table 13. Summary of Diurnal Flow Measurements**

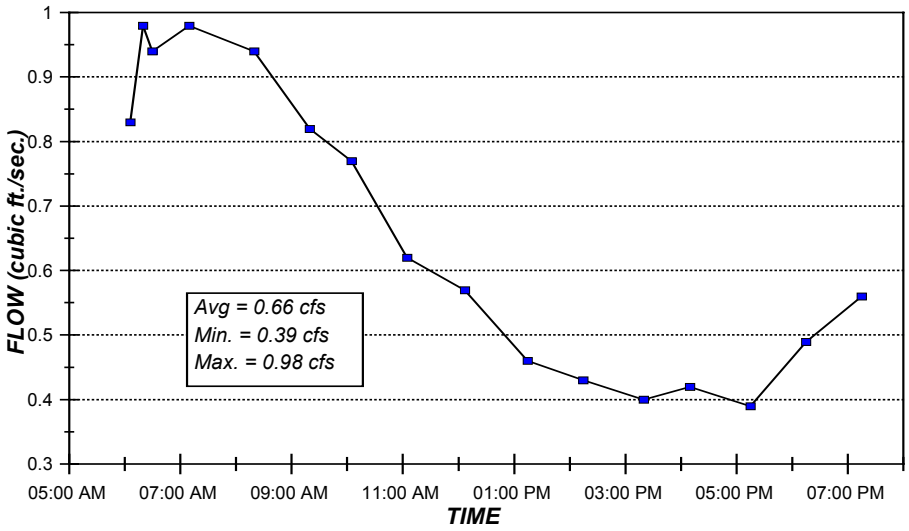
| **Del Lago Dam Site 6/22/95** | | **Del Lago Dam Site 1/12/96** | | **Del Lago Dam Site 6/18/96** | | **Marsh Sta. Site 6/23/96** | | **Marsh Sta. Site 3/18/97** | |
|---|---|---|---|---|---|---|---|---|---|
| *Time* | *Q (cfs)* | *Time* | *Q (cfs)* | *Time* | *Q (cfs)* | *Time* | *Q (cfs)* | *Time* | *Q (cfs)* |
| 6:06 | 0.83 | 7:50 | 0.56 | 5:51 | 0.34 | 6:58 | 0.50 | 6:40 | 1.84 |
| 6:20 | 0.98 | 8:40 | 0.61 | 5:59 | 0.30 | 8:22 | 0.50 | 8:01 | 1.86 |
| 6:30 | 0.94 | 9:30 | 0.59 | 7:04 | 0.29 | 9:08 | 0.49 | 9:18 | 1.79 |
| 7:10 | 0.98 | 10:35 | 0.49 | 8:02 | 0.32 | 10:04 | 0.48 | 10:36 | 1.89 |
| 8:20 | 0.94 | 11:37 | 0.69 | 9:01 | 0.26 | 11:05 | 0.38 | 11:43 | 1.78 |
| 9:20 | 0.82 | 12:30 | 0.62 | 10:03 | 0.30 | 12:22 | 0.37 | 12:49 | 1.79 |
| 10:05 | 0.77 | 13:30 | 0.65 | 11:04 | 0.26 | 13:35 | 0.31 | 13:55 | 1.85 |
| 11:05 | 0.62 | | | 12:01 | 0.28 | 14:09 | 0.30 | 14:58 | 2.11 |
| 12:07 | 0.57 | | | 13:10 | 0.25 | 15:41 | 0.27 | 15:54 | 1.90 |
| 13:15 | 0.46 | | | 14:02 | 0.26 | 16:11 | 0.26 | 17:04 | 1.93 |
| 14:15 | 0.43 | | | 15:03 | 0.24 | 16:47 | 0.27 | 18:20 | 2.0 |
| 15:20 | 0.40 | | | 16:06 | 0.24 | 18:04 | 0.27 | | |
| 16:10 | 0.42 | | | 17:10 | 0.24 | 19:16 | 0.31 | | |
| 17:15 | 0.39 | | | | | | | | |
| 18:15 | 0.49 | | | | | | | | |
| 19:15 | 0.56 | | | | | | | | |
| | | | | | | | | | |
| Avg. Q Rate | 0.66 | | 0.60 | | 0.28 | | 0.36 | | 1.89 |
| Min. Q Rate | 0.39 | | 0.49 | | 0.24 | | 0.26 | | 1.78 |
| Max. Q Rate | 0.98 | | 0.69 | | 0.34 | | 0.50 | | 2.11 |

The first three diurnal measurements were conducted within 100 yards upstream of Del Lago Dam. This site was selected for two reasons. First, the possibility of significant diurnal variations seemed high, because of the dense riparian vegetation along this reach. Second, the proximity to the Del Lago #1 well made it convenient for simultaneously conducting hourly depth-to-groundwater measurements.

The first diurnal flow measurement was conducted at the Del Lago #1 site on June 22, 1995, which was a clear, hot (100°F+) day near the summer solstice, when ET rates were probably among the highest of the year. This measurement showed significant diurnal variation in discharge (Figure 74). The flow rate decreased rapidly between about 8:00 AM and 1:00 PM, but remained fairly steady, with only a slight decrease, between 1:00 PM and 5:00 PM. Flow began increasing rapidly after 5:00 PM. The flow rate in the early morning was more than double the flow rate in the late afternoon. The difference between maximum and minimum flow rates measured was 0.59 cfs.

**Figure 74: Diurnal Streamflow Measurements**
**Del Lago Dam Site**

6/22/95

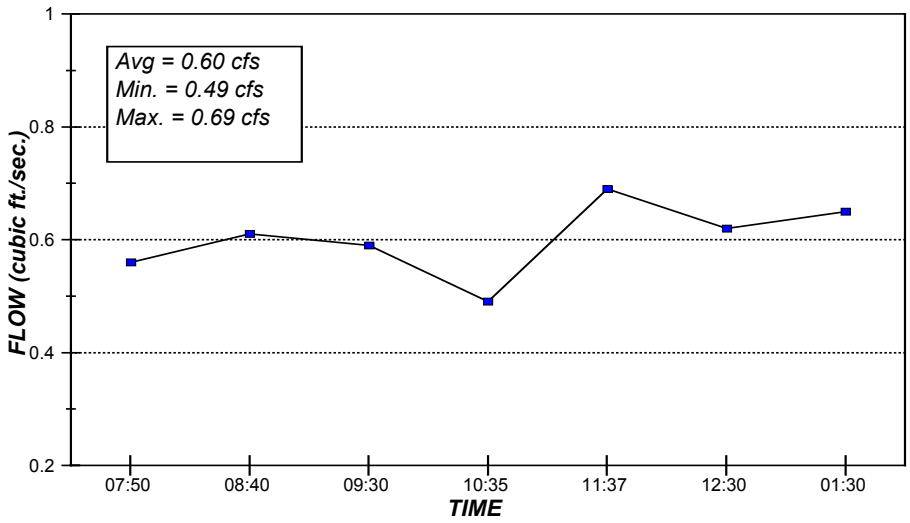



These diurnal variations were attributed to variations in the ET rate, which increased during the morning hours, as the air temperature, sun intensity, and wind speed increased and relative humidity decreased. The increasing ET reduced the volume of groundwater available to discharge into the stream, causing the streamflow rate to drop. Eventually, by early afternoon, the ET rate stabilized, and the streamflow rate remained fairly constant. Then, as the sun began to set, the ET rate dropped, and streamflow rebounded.

PAG conducted a second diurnal flow measurement at the Del Lago site during the following winter, on January 12, 1996. No significant diurnal variation in flow was seen (Figure 75). Although the weather was warm and dry (70°F+), the ET rate was much lower than in the summer, because most of the riparian vegetation was free of leaves. It was concluded that streamflow variation was minimal because the ET effects were insignificant. The measurement was terminated at about 1:30 PM because of instrument failure.

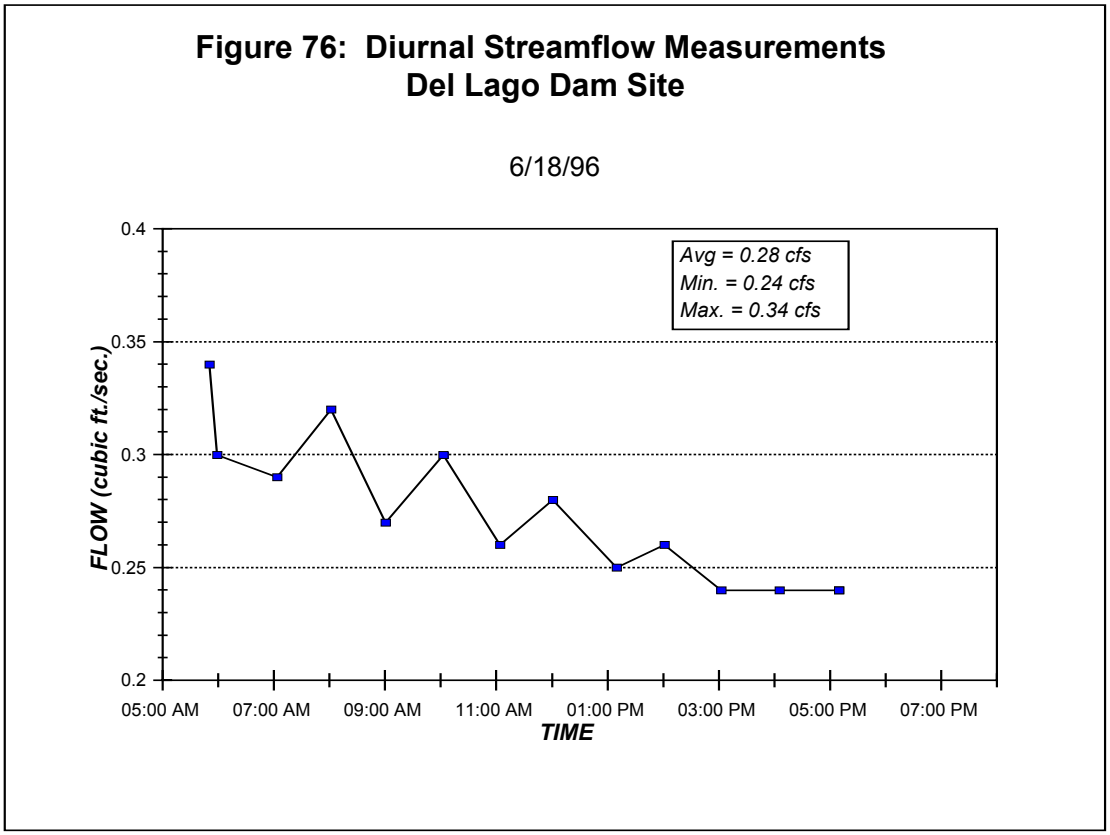
**Figure 75: Diurnal Streamflow Measurements**
**Del Lago Dam Site**

1/12/96




A third diurnal flow measurement was conducted at the Del Lago site on June 18, 1996 (Figure 76). Significantly less variation in flow was observed compared to the June 1995 measurement, with the maximum flow rate only 0.10 cfs greater than the minimum flow rate. However, an overall trend toward decreasing flow between the early morning and late afternoon was observed. The flow rate had stabilized by 3:00 PM. It is unclear why hourly measurements showed alternating increases and decreases in flow.

The diurnal variation in June 1996 was expected to be similar to the variation in June 1995, because the measurements were made at the same time of year, at the same location, and under similar weather conditions, except that June 1996 followed an unusually dry winter, whereas June 1995 followed a relatively wet winter. However, the variation in June 1996 was much less than the variation in June 1995. One likely reason was that the stream channel had been significantly disturbed by cattle. Away from the actively-flowing channel, the stream bottom was marshy and saturated with water, with a very irregular surface, and numerous, disconnected puddles and ponds. Therefore, a significant volume of surface water was present that was not included in the streamflow measurement. The extent of standing water visibly diminished throughout the day, presumably in response to increasing ET, without influencing the flow in the active stream channel. If, as was the case the previous year, the stream channel had been in better condition, with all of the surface water in the actively-flowing stream instead of dispersed across the width of the channel, the effects of ET might have been more apparent in the streamflow measurements.



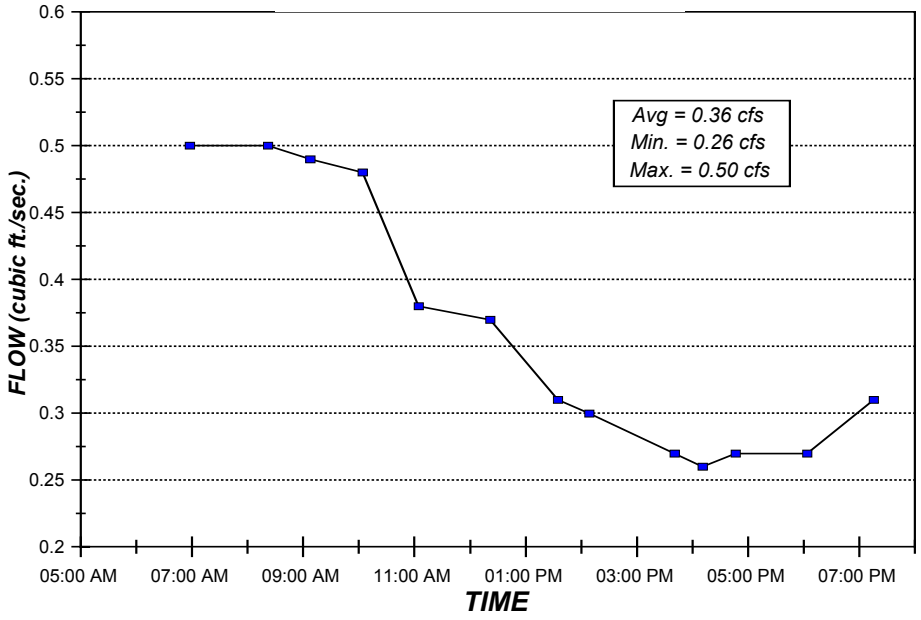

The change from relatively wet conditions in June 1995 to the dry, low-flow conditions in June 1996 might also have contributed to the decrease in diurnal variation at the Del Lago site. In June 1996, surface flow began only about 100 yards upstream from the Del Lago measurement point, whereas in June 1995, surface flow probably began a mile or more upstream. Therefore, the June 1995 measurement included the combined flow from various gaining and losing reaches upstream, and the cumulative ET effects on all of these reaches would presumably have been reflected in the measurement at the Del Lago site. The June 1996 measurement, on the other hand, included only a single gaining reach beginning about 100 yards upstream, and the measurement might only have reflected the ET impacts on this relatively short reach. If this was the case, the June 1995 measurement would have reflected a greater cumulative ET effect, and it would therefore be expected to show greater diurnal variation in stream discharge.

In order to determine whether the June 18, 1996, observation of small diurnal variations at the Del Lago site was representative of other locations on Cienega Creek, PAG conducted another diurnal measurement on June 23, 1996 at the Marsh Station bridge crossing (Figure 77). The stream channel at Marsh Station was in much better condition, with nearly all of the surface water present in the actively-flowing stream. The discharge was also much higher at this location, and streamflow began more than one-quarter mile upstream. Significant variation was observed during this measurement. Like the June 1995 measurement at Del Lago, the maximum flow rate in the early morning was nearly double the minimum flow rate in the afternoon. The maximum instantaneous flow rate was 0.24 cfs more than the minimum instantaneous flow rate. The flow rate decreased rapidly between about 10:00 AM and 3:30 PM, remained steady until around 6:00 PM, then began increasing after 6:00 PM. It was

concluded that the June 18, 1996 measurement at the Del Lago site was anomalous, and that significant diurnal variations are typical for Cienega Creek when ET rates are at a maximum.

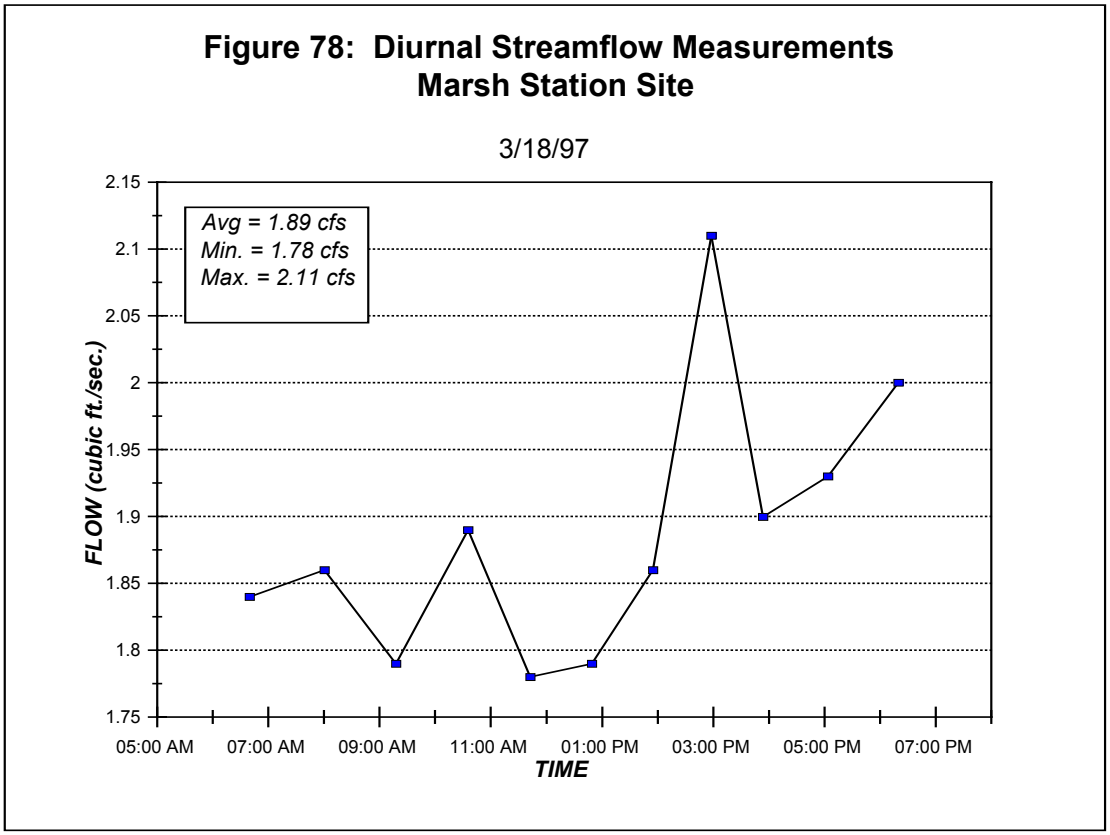
**Figure 77: Diurnal Streamflow Measurements**
**Marsh Station Site**

6/23/96




PAG conducted a fifth diurnal flow measurement on Cienega Creek on March 18, 1997, at the Marsh Station site (Figure 78). The four previous diurnal measurements had been made during seasons when ET was either at a maximum or minimum. The March 1997 measurement was conducted during a month when ET was presumably at a moderate level. The March 18, 1997, measurement indicated no consistent trend in diurnal variations. The maximum instantaneous flow rate was 0.33 cfs greater than the minimum instantaneous flow rate, but no consistent hourly trend was observed. This suggested that, at this time of year, variations in ET have a minimal effect on the flow rate in Cienega Creek.

In summary, significant diurnal variations in streamflow occurred along Cienega Creek during the summer months, but not at other times of the year. The diurnal discharge variations occurred in response to variations in evapotranspiration rates. Based on this information, it is essential that summer stream discharge measurements be made the same time of day, so that seasonal and long-term trends are not obscured by diurnal variations.




Estimates of Evapotranspiration (ET) Losses

PAG estimated ET losses from the younger alluvial aquifer using the results of the June 23, 1996, diurnal groundwater level measurement at the Cienega well. This estimate, because it was based on data collected near the summer solstice, probably represented an ET rate that was close to the maximum.

PAG used the following equation, which was developed by White (1932) and described in groundwater hydrology text books by Todd (1980) and Freeze and Cherry (1979):

$$V_{ET} = S_y\,(24h \pm s)$$

where:

$V_{ET}$ = the volume of evapotranspiration per unit area,
$S_y$ = the specific yield near the water table,
$h$ = the hourly rate of recharge, measured as the rise of the water table between midnight and 4 AM, and
$s$ = the net fall or rise of the water table during a 24 hour period.

PAG chose a value of 0.225 for specific yield, which was based on a range of 0.2 to 0.25 reported by ADWR (Kennard et al., 1988), citing a water adequacy report for the Empirita Ranch development prepared by Errol Montgomery and Associates (1985). Freeze and Cherry

(1979) recommended using an $S_y$ value that is 50% of the true specific yield, based on research by Meyboom (1967). Therefore, PAG used a value of 0.11 for $S_y$ in the equation.

PAG had only measured groundwater levels between 7 AM and 7 PM; therefore, some assumptions were necessary in choosing values for *h* and *s*. PAG assumed that the amount of recharge was negligible at the time of this measurement, because no significant precipitation events had occurred recently. Also, the water level at the well dropped by 1.34 feet between June 5 and June 29; this corresponds to an average change in water level for the period of -0.002 ft/hr. Therefore, PAG assumed that the value of *h* was zero. PAG also assumed that the net fall in the water table during a 24-hour period was equal to the net fall observed between 7:00 AM and 7:00 PM, which was 0.28 feet. Therefore, a value of 0.28 feet was used for *s* in the equation.

Using these values in the equation defined above, PAG calculated a daily evapotranspiration rate of 0.031 cubic feet per unit area. Pima County Flood Control District (1993) estimated that 570 acres (24,829,200 $ft^2$) of mature riparian woodlands were present between Interstate 10 and Vail, based on 1985 aerial photographs. Assuming that the water level fluctuations at the Cienega well were representative of this area, the rate at which groundwater from the younger alluvial aquifer is withdrawn by ET from riparian woodlands in late June would be 769,705 cubic feet/day (8.9 cfs). If, based on PAG's other diurnal groundwater level and streamflow measurements, groundwater losses due to ET are assumed to be zero between December and March, and if the increment of change in ET between March and June and between June and December is assumed to be linear, then a rough estimate of the annual average ET rate for the 570 acres of riparian woodlands between I-10 and Vail is 3.35 cfs.

PAG's diurnal stream discharge measurements indicated that only a small percentage of the total volume of groundwater lost to evapotranspiration is reflected in stream discharge. The June 23, 1996 measurement at the Marsh Station Bridge indicated that Cienega Creek discharge dropped from 0.50 cfs in the morning to 0.26 cfs in the late afternoon. If the difference between the maximum and minimum flow rates is assumed to be due to ET losses, then the maximum rate at which water was lost from the stream at Marsh Station was 0.24 cfs, or roughly 2.7% of the total ET rate calculated from the June 23, 1996 groundwater level measurements. This is somewhat higher than a rough estimate of an ET rate of 0.10 cfs, based on the diurnal discharge measurements at Del Lago on June 18, 1996, and significantly lower than the estimate of 0.59 cfs based on the diurnal discharge measurement at Del Lago on June 22, 1995.

The relatively low ET loss observed in stream discharge is consistent with the observation that the area of the wetted stream channel is a relatively small percentage of the total area influenced by riparian ET. The length of the reach of Cienega Creek from Tilted Beds to Marsh Station is approximately 23,230 feet, roughly 21,730 of which typically exhibits base flow, based on historical data reported by PCDOT&FCD (1993). A reasonable estimate of the average width of the wetted stream channel is 50 feet or less. Thus, the area of the active stream channel from Tilted Beds to Marsh Station is probably less than 1,086,500 $ft^2$. This equates to less than 4.4% of the total area of riparian woodland contributing to ET, and an even lower percentage of the total area of younger alluvium.

PAG's estimated ET rate of 3.35 cfs is somewhat higher than the ET rate of 2.4 cfs calculated by PCFCD (1993) and used in the Chong-Diaz (1995) hydrologic model of lower Cienega Creek. The PCFCD estimate was based on an assumed average of 3 AF per year, per

unit area of riparian woodland. According to the sensitivity analysis conducted by Chong-Diaz (1995), the model's sensitivity to ET was low in terms of groundwater levels, but high in terms of stream discharge, for ET factors less than 2 (i.e., ET less than twice the value used in the model). Therefore, if PAG's value for ET was used in the model, the predicted stream discharge values might be significantly affected, but the predicted groundwater levels would not.

Additional data are needed to determine if PAG's estimate of ET is valid. Several assumptions were used to make this estimate. The most tenuous of these included the assumption that groundwater level changes observed in the June 1996 diurnal measurement at the Cienega well were representative of the whole preserve, and the assumption that ET rates varied linearly with time between March and June and between June and December. Additional diurnal measurements at several wells, and at various times of the year are needed to obtain a more reliable ET estimate. The measurements should also be for a 24-hour duration. The area of riparian woodlands should also be recalculated using more recent aerial photographs.

# VIII. COMPARISON OF CHONG-DIAZ MODEL RESULTS TO PAG MONITORING PROGRAM

One of the purposes of this report was to evaluate whether PAG's monitoring program was adequate to detect any impacts on the Cienega Creek Natural Preserve from upstream pumping at the Empirita Ranch development. A significant amount of research, including several Master of Science theses, has been conducted at the University of Arizona Department of Hydrology and Water Resources to predict what the impacts of the pumpage, if any, will be. One of the theses was a groundwater flow model prepared by Damaris Chong-Diaz. Chong-Diaz used the finite-element model *MODXX,* which employs mathematical solutions to partial differential equations that describe transient flow through a saturated, non-homogeneous, anisotropic porous medium. This program has a similar data structure to *MODFLOW*, a groundwater flow model developed by the U.S. Geological Survey. PAG reviewed the results of this model to determine whether any changes were needed to the current monitoring program.

Empirita Ranch was originally designed to be a master planned retirement community located on approximately 8,000 acres southeast of the Cienega Creek Natural Preserve. The community would have included commercial, medical, and recreational facilities. In addition, a resort hotel and three eighteen-hole golf courses were included in the overall design plans, although only two of the golf courses were to be constructed under Stage One of the proposed development process. A sand and gravel operation was also slated to operate on approximately 80 acres south of I-10, and directly west of Cienega Creek. However, since 1985 when Stage One development plans were outlined in the 1985 Errol L. Montgomery & Associates report entitled *Water Adequacy Report Stage One Development Empirita Ranch Area Pima County, Arizona,* several changes have been made to the development design, and in property ownership.

## Background and Description of Proposed Empirita Development

In November 1986, the Pima County Flood Control District Board of Directors passed resolution 1986-10, which set the original boundaries for the Cienega Creek Natural Preserve. The purpose of the preserve, as stated by the Board, was "to conserve riparian habitat, increase flood storage, reduce flood peaks, increase groundwater recharge, and to prevent unwise and detrimental use of the Cienega Creek floodplain." By 1990, most of the properties targeted for acquisition by Pima County Flood Control District (PCFCD) had been purchased from various private owners, including 310 acres bought from Empirita Ranch, Inc. in January of 1989 (PCDOTFCD, 1990).

The Pima County Board of Supervisors realized at the time the preserve was created the importance of linking Cienega Creek Natural Preserve with the Bureau of Land Management's Empire-Cienega Resource Conservation Area (RCA) located approximately six miles south of Interstate 10. Linking the two areas, together with further acquisitions to the north, would create a continuous corridor of open space from the U.S./Mexico border to the town of Oracle, approximately 90 miles to the north (PCDOTFCD, 1990). This would be consistent with the Pima County Comprehensive Plan adopted by the Board of Supervisors in September 1989, as well as the Open Space Plan developed in 1988. In 1987, the county identified a minimum of 4220 acres needed to complete this objective. In July 1990, the Pima County Board of Supervisors approved the purchase of two additional properties within Empirita Ranch comprising a total of 880 acres. The newly-acquired property allowed the preserve to extend south of I-10, encompassing portions of Cienega Creek's upper reach (PCDOTFCD, 1990).

As a stipulation included in the acquisition of the Empirita Ranch properties, Empirita Ranch would retain the certificate of adequate water supply for 1600 acre-feet per year as issued by the Arizona Department of Water Resources. This is the permanent maximum limit of groundwater that would be allowed to be withdrawn from the Cienega Creek aquifer in order to support the proposed development (PCDOTFCD, 1990). Sixteen wells have been approved to be drilled in the Empirita Ranch area to withdraw this groundwater, although final locations of wells have yet to be specified. In addition, it was specified that this groundwater could only be used to supply the areas of private property included in the area plan, and water could not be sold or transferred outside of the area plan. Pima County further stipulated that the county would monitor pumping from area wells to ensure that the riparian habitat of Cienega Creek would not be irrevocably harmed (PCDOTFCD, 1990).

The Pima County Comprehensive Plan was revised in October 1992 and December 1996, and included Regional and Special Area Plan Policies for the Empirita Ranch Area Plan (ERAP). This Special Area plan set guidelines affecting the development and design of the planned community. The 1985 Errol L. Montgomery & Associates report included Appendix D entitled *Details for Water Requirements, Stage One Development, Empirita Ranch*, which was prepared by Dooley-Jones & Associates. This report detailed the preliminary development plans for the area. However, many changes were made due to the changes in land ownership and in order to be consistent with the new Comprehensive Plan effective as of December 1996 (Pima County Development Services Department, Planning Division, 1996).

The Special Area Plan Policies included Performance and Design Criteria which should be fully addressed at the Specific Plan level. Criteria included "above-standard flood control improvements on both on-site and off-sites locations, and exceptional employment of water conservation measures, including, but not limited to, above-standard landscaping involving use of low water-consuming native vegetation, restoration/reclamation, and preservation of existing vegetation" (Pima County Development Services Department, Planning Division, 1996).

Under the Land Use Policies section, the number of dwelling units permitted for this Special Plan Area would not exceed 4,200 units. The maximum dwelling cap was based on two identified communities within ERAP which lie within the Special Area borders. ERAP Community 2 would be located in the eastern portion of the Special Area, and would contain a minimum of 2,500 and a maximum of 3,000 dwelling units. Community 2 would be developed as a mixed residential community with provisions to promote on-site employment opportunities. ERAP Community 5 would be located south of I-10 in the western portion of the Special Area. A minimum of 400 and a maximum of 1,200 dwelling units were designated for this area located closest to the upper reaches of Cienega Creek. Community 5 would be developed as a retirement community. Non-residential uses such as commercial, office, campus park industrial, and light industrial uses were designated to not exceed 5% of the total Special Area. However, this is subject to the performance objective of increasing on-site employment opportunities. In addition, the area south of I-10 (ERAP Community 5) would also have a maximum of 5% of the area planned for commercial and office uses. Additional requirements would be developed during in-depth studies in the following areas: flood control, wastewater control, water, transportation, paths/trails and open space, parks, turf and irrigation, fire protection, screening and buffering, and schools. The location of the proposed development is shown on Figure 79.

Findings of the Chong-Diaz Model

The Chong-Diaz model assumed that the Empirita Ranch development would withdraw 1,600 acre-feet of groundwater per year (2.2 cfs) as allotted by ADWR, and that this water would be obtained from two wells drilled into the younger alluvium. These wells were assumed to be located between the Narrows and the Jungle Road Site. Ephemeral stream recharge from stormflow events was not included in the model. Therefore, the results represented the effect of pumpage during very dry years.

The Chong-Diaz model employed a finite element grid structure which was conformed to fit the stream's individual characteristics. In the model, Cienega Creek was divided into 32 reaches, with each reach in the grid assigned a numbered node. Node 1 was located at the western edge of the preserve, near the Del Lago dam. Node 32 was located at the Bootlegger well, located approximately one mile downstream of the Narrows. The grid represented a study area encompassing 100 square miles. Two wells, pumping a combined total of 2.2 cfs, were assigned locations near the Empirita Ranch Headquarters at nodes 24 and 25. Hydraulic conductivity values of 4000 gpd/ft$^2$ to 6800 gpd/ft$^2$ for the alluvial deposits aquifer, and 6000 gpd/ft$^2$ for the basin fill aquifer, were obtained from Errol Montgomery Associates (1985).

The model included simulations of current conditions (i.e., steady state) and conditions after pumping at Empirita Ranch begins (i.e., transient state). Seasonality effects were introduced into the model to observe the effects that pumping would have during particular time periods; therefore, the simulations are referred to as “oscillatory” (i.e., steady oscillatory state and transient oscillatory state). The seasons were defined as follows: season 1- December through March, season 2- April through June, season 3- July through September, and season 4- October through November. Seasons 1 and 3 were defined as wet seasons, while seasons 2 and 4 were defined as dry. The steady oscillatory state simulation accurately portrayed the stream's current conditions. The results were used as a base to compare the effects of future pumping simulated in the transient runs. Conditions after one year of pumping and nine years of pumping were simulated.

After one year of pumping 2.2 cfs from the younger alluvium, the transient oscillatory state (TOS) simulation predicted that an overall reduction in streamflow of approximately 36% would occur. All reaches with perennial flow would be affected. Also, the TOS run, for each season, showed that one gaining reach was lost compared to the steady state oscillatory simulation. In each case, the gaining reach which was lost was reach 19, which roughly equates to the area of Cienega Creek upstream of Marsh Station Bridge. During the TOS run, the largest drawdown after one year of pumping occurred at the well located at node 24, near the Empirita Ranch Headquarters. The TOS simulation calculated a cumulative 7.46 ft. drawdown for this well. Seasons 1, 2, and 4 displayed a drawdown only in the vicinity of the pumping. However, season 3 (July-September) showed drawdown at the pumping site, and at nodes 3 to 5, and 31. Nodes 3 to 5 equate

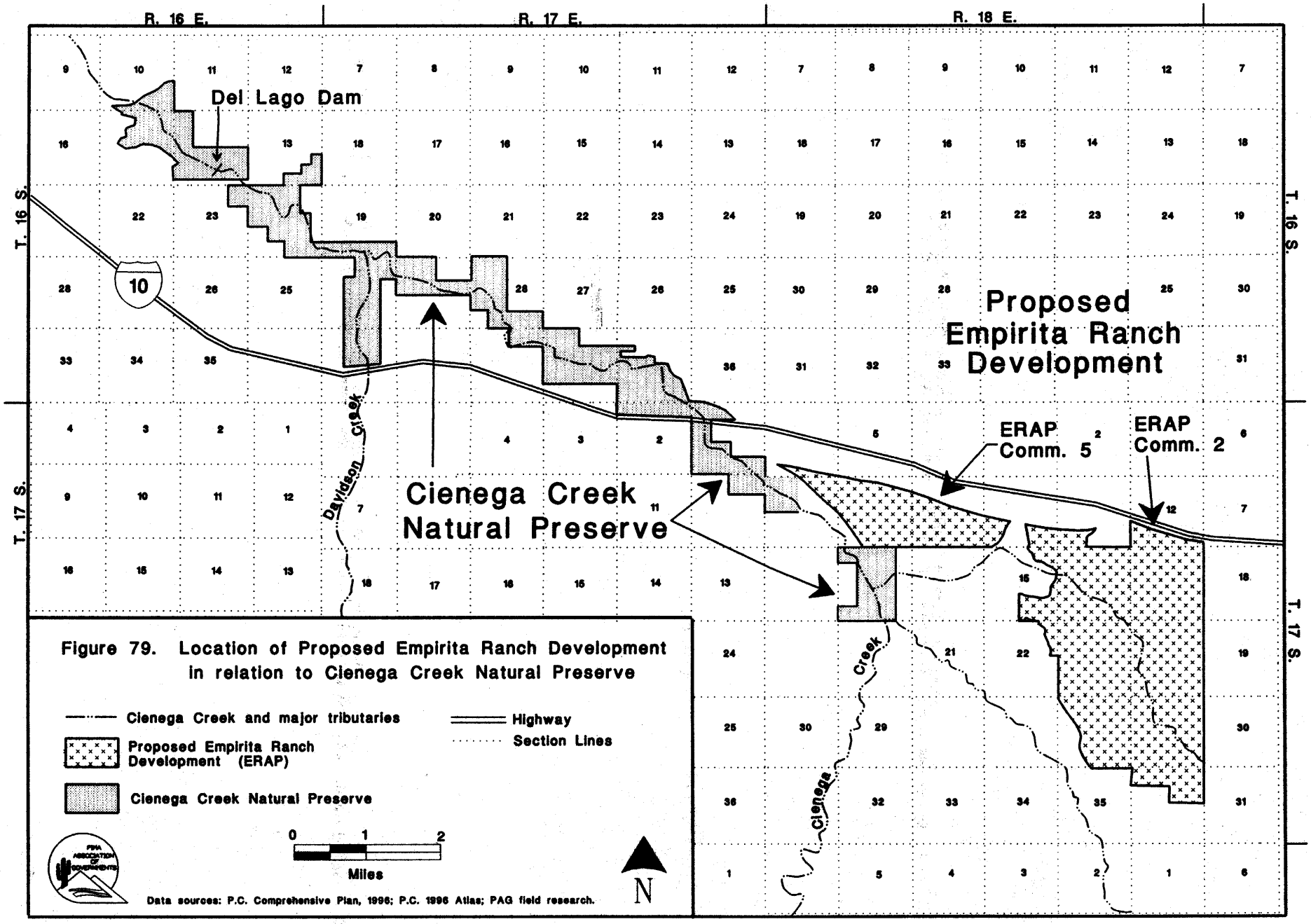



Figure 79. Location of Proposed Empirita Ranch Development in relation to Cienega Creek Natural Preserve

to the area located upstream of the Del Lago dam at the SP # 1006 site to near the Marsh Station Bridge/Cienega Creek crossing, and node 31 represents the area directly downstream from the Bootlegger well. As of April 1997, PAG's Cienega Creek monitoring program included streamflow extent monitoring at the SP #1006 monitoring site, as well as stream discharge measurements upstream of the SP #1006 site at the Marsh Station Bridge site. A decrease in perennial surface flow after one year of pumping at the planned Empirita Ranch development should be detected at these monitoring locations. However, the reach downstream from the Bootlegger well, which is about five mile south of I-10, is not currently monitored by PAG.

After nine years of pumping 2.2 cfs from the younger alluvium at the proposed Empirita Ranch development, the model predicted that reaches 12 through 15 would experience a 100% reduction in flow, indicating that most of the reach of Cienega Creek between the Jungle Road site and the Cienega well would lose perennial flow. PAG's Tilted Beds monitoring site is located within this reach. A reduction of nearly 90% after nine years of pumping was predicted for reaches 5 and 6, which include PAG's Marsh Station Bridge and Cienega/Davidson confluence monitoring sites.

The model predicted that after nine years of pumping, groundwater level drawdowns in the younger alluvium would extend downstream as far as node 3, which is near the SP #1006 streamflow extent monitoring site. The most significant drawdown would extend downstream as far as reach 16, located near the Jungle Road site. The Jungle, Empirita #1, and Empirita #2 wells are within this area, and should therefore show impacts from the pumping if the current monitoring program was continued. However, the Empirita #2 well is drilled into the Pantano formation, and water levels at this well might not reflect the impacts of the drawdown on the shallow alluvial aquifer.

The reliability of groundwater flow modeling results is typically limited by a number of factors. Limitations of the Chong-Diaz model appear to include a lack of field data for vertical conductance, a paucity of wells and drillers logs, limited information about locations of subsurface bedrock highs (which strongly influence the locations of surface flow), and a need for additional field data for hydraulic conductivity and seasonal evapotranspiration rates.

The model was also based on relatively limited stream-discharge data that did not include recent discharge data collected by PAG (Maddock, 1998). This led to discrepancies between simulated baseline flows and flows observed by PAG. Specifically, flows observed by PAG were significantly lower in some reaches than the flows predicted in the model's steady-state simulation. In fact, during the summer of 1996, PAG observed certain reaches, which had previously flowed year-round, going dry. This occurred during non-pumping, drought conditions, which are the steady-state conditions that the model was supposed to simulate. However, the model predicted steady-state discharges of at least 0.5 cfs for all reaches downstream of Jungle Road. Because the model overestimated discharge along certain reaches during non-pumping conditions, it seems possible that the model also overestimated discharge along these reaches during pumping conditions. Therefore, streamflows after pumping begins could be even lower than the model predicted. However, additional simulations using revised data are needed to verify this. Data used in these simulations should reflect the effect that drought conditions have on the impacts of ET. According to Professor Tom Maddock, a groundwater modeling expert at the University of Arizona, ET could have a more significant impact on base flows in Cienega Creek during drought conditions (Maddock, 1998).

Assuming that, despite the limitations, the model accurately predicts the impacts of future groundwater withdrawals on groundwater and surface water in the Cienega Creek Natural

Preserve, PAG's monitoring program as of April 1997 would adequately identify these impacts. One possible improvement to the program would be to reinstate the streamflow observations at the Cienega well, because this location is near the downstream limit of the reach that is predicted to go dry after nine years of pumping.

The Chong-Diaz model predicted that long-term pumpage at a rate of 2.2 cfs from the younger alluvium near the proposed Empirita Ranch development would have severe hydrologic impacts on lower Cienega Creek, including water table declines and loss of perennial flow. These impacts would adversely affect wildlife and riparian habitat in the preserve.

If the model is valid, alternative plans for the development should be considered, including acquisition of alternative water sources. Otherwise, impacts from the development could be contrary to goals identified in the *Regional and Special Area Plan Policies* of the *Pima County Comprehensive Plan* (Pima County Development Services Department, 1996). Under section B of these policies, entitled Natural and Cultural Resources, the Wildlife Habitat and Corridors section states, "Regional wildlife plan policies support Conceptual Land Use Element (CLUE) policy objective #27, which states, 'Measures will be taken by the county to insure zero loss of any wildlife species within the region, especially endangered or threatened species. Existing riparian habitat shall be protected.' These regional policies are intended to recognize the value of Pima County's wildlife resources by protecting significant habitat and fostering the unimpeded movement of wildlife. Protection of wildlife habitat and corridors includes preservation and mitigation of negative impacts of development."

Because of the potentially significant economic consequences associated with acquiring alternative water sources, the model should be thoroughly reviewed to determine whether it is likely to accurately predict the impacts from pumpage. The future investigations recommended by Chong-Diaz should also be conducted. These include field studies to obtain specific locations of subsurface bedrock highs, parameters such as ET, hydraulic conductivity, and streambed conductance, and future simulations that include recharge from ephemeral streams.

# IX. SUMMARY OF CIENEGA CREEK RESEARCH AND OTHER PERTINENT RESEARCH RELATED TO RIPARIAN ENVIRONMENTS

Cienega Creek has been the focal point of many research projects completed by University of Arizona graduate students, private consulting firms, and various governmental agencies. PAG reviewed and summarized a variety of reports related to these projects, so that the information would be readily available for future studies. Additional reports not specifically involving Cienega Creek were also summarized if the information presented was pertinent to the general understanding of riparian environments. This section summarizes the purpose and conclusions presented in each report, as well as the type of data included.

1. *Geology and Geophysics of the Cienega Basin Area, Pima and Cochise Counties, Arizona*
   By Stephen M. Richard and Raymond C. Harris
   Arizona Geological Survey Open-File Report 96-21
   1996

   Arizona Geological Survey Open-File Report 96-21 discussed detailed structural characteristics of the Cienega Creek basin. Two sets of magnetic data were used to preliminarily define the subsurface geology. Gravity data compiled by E. Roudebush (1996) were analyzed, and seven gravity stations used by Roudebush in his master's thesis were ultimately rejected from this study due to discrepancies between the grid and measured values. By not including these stations, unreasonably large gravity gradients were avoided.

   In comparing the basin thickness isopach maps produced by Ellett (1996) to those developed by this study, it was determined that the isopachs were generally similar, except for the 1200 ft. contour which Richard and Harris felt enclosed a larger area. Also, a fault on the west side of the Narrows was found to offset the isopachs in the southern part of the basin. This report also did not concur with Ellett's interpretation of a 1800 ft. deep sub-basin on the west side of the Narrows structural high. In addition, sub-basins which occur to the east of the eastern Cienega-basin-bounding bedrock ridge were interpreted as being deeper than was found by Ellett.

   Overall, this report presented a detailed structural interpretation of lower Cienega basin. Several maps for the area were included: a detailed geologic map, a complete Bouguer gravity anomaly map, an aeromagnetic anomaly map, and an aeromagnetic map.

2. *Water Resources Management of Riparian Area in the Upper Cienega Creek- A Progress Report*
Prepared by Thesis Practicum Class, Hydrology 694 A,B; Department of Hydrology and Water Resources, University of Arizona
1996

This document summarized the progress of a group project researching water resources and general hydrology of the Cienega Creek basin conducted by a team of graduate students from the Department of Hydrology and Water Resources at the University of Arizona. The first team of students addressed the lower basin, while the second team focused on upper Cienega Creek basin. The second team applied information and models generated from the first group of students in order to develop an integrated water management approach for the entire Cienega Creek basin.

To date, three of the six theses originating from this practicum have been completed. Those that have not been completed are summarized below, while completed theses are addressed as individual works listed later in this section.

*Hydrogeochemical Modeling of Western Basin Groundwater Recharge*
A thesis in progress by Hans Huth

The purpose of this thesis was to compile data from previous studies in order to develop a geochemical model to identify the natural processes which control water quality in the upper Cienega basin. Three main flow paths were preliminarily identified: Sawmill Canyon fault zone, the axis of Gardner Canyon, and the axis of Oak Tree Canyon.

In the Sawmill Canyon fault zone, the flow path was through 4 miles of carbonate rock. This path was characterized by an increase in concentration of all major cations and anions, except for sodium, along the hydraulic gradient. This is characteristic of the dissolution of calcite, dolomite, and pyrite. The Gardner Canyon flowroute showed a dilution of groundwater from infiltrating waters demonstrated through changes in chloride concentration, undersaturation of calcite and dolomite, and an increase in pH. Dissolution of calcite was found; this was interpreted as an attempt by infiltrating waters, which were depleted in dissolved carbonate minerals, to compensate for the dilution of groundwater. In Oak Tree Canyon, a lack of data from wells drilled into the shallow aquifer limited conclusions. A decrease in pH was found to be due to $CO_2$ dissolution through root zone respiration and decaying organic matter. Increases in magnesium and calcium were attributed to dolomite dissolution. Further field sampling was scheduled to be conducted in this area.

*Modeling of Stream-Aquifer Interaction in Upper Cienega Creek Basin*
by Liciniu Bota

The author is using a modular three-dimensional, finite difference groundwater flow model (MODFLOW) to investigate the interaction between the surface and groundwater in the upper Cienega Creek basin. No conclusions have been determined.

*Modeling of Stream-Aquifer Interaction in both the Upper and Lower Cienega Creek Basins*
by Dee Korich

The purpose of this study is to evaluate future groundwater development in the upper and lower Cienega Creek basins by combining the thesis work done by Chong-Diaz (1995) and Bota (see above). In order to do this, the entire basin will be remodeled using MODFLOW. A steady state model is to be calibrated, and several pumping scenarios will be introduced to model the impact of streamflows during both wet and dry seasons. Also, a ten year development scenario will be simulated.

3. *A Water Budget and Land Management Recommendations for Upper Cienega Creek Basin*
Erik Lloyd Knight, Master's Thesis submitted to the Department of Hydrology and Water Resources, University of Arizona
1996

This thesis was completed in conjunction with the Cienega Creek Group Thesis Practicum Project developed by the Department of Hydrology and Water Resources at the University of Arizona. The focus of this study was to develop a water budget for the upper Cienega Creek watershed, and to evaluate various water and land management policy options.

An average annual water budget was developed in order to avoid any difficulties related to seasonal fluctuations. A surface and subsurface water budget for upper Cienega Creek was combined to form an overall water budget for the basin. Several parameters were not applicable to this basin, and therefore were set to zero. All other terms were estimated through research done by the author, or other members of the Cienega Creek Group Project. Precipitation was assumed to be the only source of input into the watershed since no other surface or groundwater source is known to contribute to the basin. Regional precipitation data from the U.S. Weather Bureau were collected, and it was assumed that the primary factor influencing areal differences in precipitation was elevation.

Surface and groundwater outflow from the upper basin occurred at a bedrock high (the Narrows). Groundwater outflow also occurred due to pumping withdrawals. The author noted however, that evapotranspiration was the major process accounting for water leaving the basin. Estimated evapotranspiration from riparian areas and from grasslands was contributed by another Cienega Creek Group Project member, Mark Williams. From Williams' model, it was concluded that the grassland evapotranspiration rate equals the precipitation rate. The model was not capable of determining evapotranspiration from riparian areas, so a potential upper limit riparian

evapotranspiration rate was used. By subtracting all the various sources of outflow from the only source of inflow, precipitation, it was concluded that the basin aquifer was experiencing a net loss of 644 acre-feet per year.

It was further concluded that perennial flow in upper Cienega Creek would not be affected by growth in the towns of Sonoita and Elgin since most of the land in the upper basin, and the associated water rights, are owned by BLM. However, if any substantial groundwater development occurred in the Cienega basin, it could have dramatic, negative affects on streamflow and riparian habitat in upper and lower Cienega Creek. Several management recommendations were made for upper Cienega Creek, including federal protection under the Wild and Scenic River Act, and protection under state programs such as Unique Waters designation and Instream Flow rights.

4. *Atmospheric Exchanges of Riparian Vegetation in a Semi-arid Environment*
Omer Lutfi Sen, Master's Thesis submitted to the Department of Hydrology and Water Resources, University of Arizona
1996

The purpose of this thesis was to study the interaction between the rate of photosynthesis uptake and the rate of transpiration occurring in a semi-arid tall riparian environment. There were three specific objectives addressed. The first was to record, for an extended period of time, simultaneous measurements of carbon dioxide exchange and water vapor loss from riparian vegetation. The second objective was to examine the overall carbon dioxide exchange, and to identify the specific contributions of photosynthesis and respiration. The third objective was to analyze the seasonal trend of daily total photosynthesis with the measured transpiration. The developed model was then compared to the known characteristics of the riparian habitat being studied to determine compatibility.

The study area defined for this project was located within the Upper Santa Cruz Valley, ten miles north of Nogales, Arizona, and 2.5 miles north-northeast of the Nogales International Wastewater Treatment Plant on the west bank of the Santa Cruz River. The vegetation in the area primarily consisted of mesquite bosques and stands of cottonwoods.

Eddy covariance measurements of energy, momentum, and carbon fluxes were collected from July 1995 to April 1996, although periods of data collection were inconsistent due to technical problems. In order to study and analyze the information gathered, a Global Circulation Model (GCM) entitled the Simple Biosphere (SiB2) Model was used. However, since many key parameter values were not available for the type of vegetation occurring in the study area, re-parameterization of the model was necessary.

The primary conclusion of this study stated by the author was, "...the observed canopy conductance has an approximately linear relationship with canopy photosynthesis, this being consistent with the assumption that the concentration of carbon dioxide inside the leaves is approximately a fixed proportion of that outside. Moreover, the semi-empirical relation between the canopy conductance and canopy photosynthesis assumed in SiB2 is far less consistent with the observed data for riparian vegetation at this semi-arid site." The study also concluded that the riparian vegetation studied is a small source of atmospheric carbon dioxide, that the division of energy between latent and sensible heat

fluxes was strongly linked to the availability of groundwater, and that atmospheric conditions, particularly high vapor pressure deficits, have a daily affect on riparian vegetation. It was concluded that photosynthetic uptake was usually limited to the early morning hours.

5. *The Influence of Bedrock on Perennial Streamflow in the Upper Cienega Creek Basin, Pima County, Arizona*
Eric Mitchell Roudebush, Master's thesis submitted to the Department of Hydrology and Water Resources, University of Arizona
1996

This thesis was completed in conjunction with the Cienega Creek Group Thesis Practicum Project developed by the Department of Hydrology and Water Resources at the University of Arizona. The focus of this research was to study the relationship between perennial flow in Upper Cienega Creek and the depth to bedrock in the basin. The author conducted a gravity survey, and combined this information with results from previous surveys. A Bouguer anomaly map was constructed from the gathered data, as were several gravity profiles for various areas within the upper basin.

The author's results both support and contradict the hypothesis that the amount of perennial streamflow was controlled by the location and depth to bedrock. The author did identify, through his gravity studies, a bedrock trough trending northeast into the San Pedro River Valley, which was originally noted by Ellett (1994). However, no conclusion was made as to whether this feature was directing groundwater from upper Cienega Creek to the San Pedro River basin or to lower Cienega Creek.

6. *Evapotranspiration in Southeast Arizona Semi-arid Watersheds: Walnut Gulch and Cienega Creek*
Mark David Williams, Master's thesis submitted to the Department of Hydrology and Water Resources, University of Arizona
1996

This thesis was completed in conjunction with the Cienega Creek Group Thesis Practicum Project developed by the Department of Hydrology and Water Resources at the University of Arizona. Williams' study focused on the development and calibration of two simple evapotranspiration models, the Priestley-Taylor and the Penman-Monteith, for application in the semi-arid Cienega Creek watershed. Since data for the Cienega Creek Watershed is limited, models were needed which had few data requirements and parameters which would need little calibration. Therefore, these models were chosen and calibrated using data from the Walnut Gulch experimental watershed. The overall goal of the research was to use the Priestley-Taylor and Penman-Monteith models to describe the daily, monthly, and seasonal cycle of evapotranspiration in the Cienega Creek watershed.

The author determined that the evapotranspiration and precipitation essentially summed to zero for the grasslands of upper Cienega Creek basin. It was concluded that the riparian evapotranspiration flux effectively represents the net evapotranspiration loss from the basin. This flux was the most difficult to estimate since micrometeorological techniques for tall vegetation like the cottonwood were inadequate. Since tall riparian

vegetation commonly occurs on streambanks and lacks an extensive, uniformly characteristic area, transpirative fluxes are not measurable by traditional micrometeorological techniques.

It was further concluded by the author that the models which were calibrated as part of this study were not applicable to riparian habitats since they were based on the assumption that the exchange of moisture occurred only by the evaporation from the soil to the atmosphere and through transpiration from vegetation. The model further assumed that the vegetation response was dictated by the amount of available soil moisture which is replenished by precipitation. This however, would not be true in a riparian habitat like Cienega Creek.

The author computed an estimated upper limit of transpiration losses for stream side mesquite groves of 583 mm for the Penman-Monteith model, and 602 mm for the Priestley-Taylor model. The models confirmed, for Cienega Creek basin, the relative balance between precipitation and evaporation. However, many assumptions were made including that the area was a semi-arid grassland. The project's conclusions agreed with assumptions made by previous investigators of the Cienega Creek area.

7. *A Hydrogeochemical Evaluation of the Lower Cienega Creek Sub-Basin, Pima County, Arizona*
Howard Lance Grahn, Master's Thesis submitted to the Department of Hydrology and Water Resources, University of Arizona
1995

This thesis was completed in conjunction with the Cienega Creek Group Thesis Practicum Project developed by the Department of Hydrology and Water Resources at the University of Arizona. Mass transport modeling of groundwater and surface water, as well as NETPATH modeling, were used in this thesis to chemically characterize the waters of Cienega basin. These models were also employed to identify and evaluate the aquifer processes which produce and control Cienega Creek's chemistry. Water quality data for all spring, well, and surface water data collection sites taken by the author from the period of April 1994 to June 1994 are included in Appendix I of the thesis. Additional water quality data provided by Errol Montgomery & Associates for the period of June 1985 to November 1993 are included for various well and surface water data collections points. Historical data provided by the U.S. Geological Survey is referenced in Appendix II of the thesis.

It was concluded that the source of lower Cienega Creek surface water was upstream basin groundwater. The data suggested that the water recharged as a calcium-bicarbonate type water derived from the slopes of the Santa Rita, Whetstone, and Empire Mountains. As the water recharged into the upper portion of the basin, it followed the natural hydrologic gradient and evolved into a calcium-sulfate type water. It then was blocked by subsurface bedrock near the Jungle Road site, where it rose to become surface flow, thus creating the headwaters of the Cienega Creek Natural Preserve.

8. *Modeling of Stream Aquifer Interaction in Lower Cienega Creek Basin Using a Finite Element Technique*

Damaris Chong-Diaz, Master's Thesis submitted to the Department of Hydrology and Water Resources, University of Arizona
1995

This thesis was described in Section VIII of this report.

9. *Cienega Creek Natural Preserve Management Plan Background Report*
Prepared by McGann & Associates Inc. for Pima County Department of Transportation and Flood Control District.
1994

This document described the current management plan for the preserve, and provided an overview of the regional setting and local conditions, as well as background and historical information. The report included a detailed site map for the preserve, a Regional Open Space Network map, a historic site location map, and figures showing local conditions such as land use and ownership, zoning, area trail system, vegetation, wildlife habitat, soils, and geologic features. A comprehensive review of the preserve's biological and physical resources comprised a large portion of this report. Vegetation, including the existing nine plant associations ranging from desert and scrubland to subtropical riparian forests, were described in detail. In addition, lists of mammals, birds, fish, reptiles and amphibians known to be present in the preserve were included. Other subjects addressed included groundwater hydrology, surface water hydrology, and an overview of existing development within the preserve such as the Southern Pacific Railroad, roads and buildings, fences and gates, stream gage stations, and utilities.

10. *Cienega Creek Natural Preserve Management Plan*
Prepared by McGann & Associates Inc. for Pima County Department of Transportation and Flood Control
1994

This document identified objectives, policies, and actions that were scheduled to be taken in relation to the management of Cienega Creek Natural Preserve. The *Cienega Creek Natural Preserve Management Plan Background Report* was prepared in conjunction with this report, and was referenced in this report as an appendix.

The *Cienega Creek Natural Management Plan* outlined and discussed the management objectives of the preserve. These objectives included preservation of the perennial stream flow and the riparian community, as well as provisions for public use. The report also included the following sections: management zones, proposed development, administration and staffing, public use, resource management, wildland fire management, the preserve boundary, and inter-departmental and inter-agency coordination.

11. *Geologic Controls on the Occurrence and Movement of Water in the Lower Cienega Creek Basin*
William Jess Ellett, Master's Thesis submitted to the Department of Hydrology and Water Resources, University of Arizona
1994

This thesis was completed in conjunction with the Cienega Creek Group Thesis Practicum Project developed by the Department of Hydrology and Water Resources at the University of Arizona. The author's goal was to better understand the configuration of bedrock in lower Cienega Creek basin, and to see how it influenced the movement and occurrence of both groundwater and surface water. The interaction between groundwater and surface water was also examined.

The author referenced past and on-going research related to the area, especially regarding estimates of mountain-front recharge affecting the Cienega Creek basin. A temperature and electrical conductivity profile was conducted to provide a better understanding of the interaction between surface and groundwater. Streamflow temperature and conductivity data were collected every 250 ft., from the Cienega Creek crossing at the Hanna's residence (the Jungle Rd. crossing) to just past Davidson Canyon. The data were graphed, and showed a general warming trend as the surface water flowed downstream. It was determined that there was a correlation between sudden changes in water temperature and the geologic characteristics of a particular site. The data suggested that a decrease in surface water temperature occurred when a bedrock outcrop or fault was located in the area of the sampling point, possibly because the fault provided a "conduit for the discharge of cooler groundwater to the surface stream." A similar situation was suspected with the bedrock outcrops because the less permeable Pantano formation and andesite outcrops forced cooler groundwater to the surface.

The author also conducted a gravity survey that resulted in a Bouguer Anomaly map. This survey provided further documentation that groundwater was being forced to the

surface in areas of perennial flow by outcrops of bedrock near, or at, the surface. Also, through gravity modeling, the author noted a possible east-west trending bedrock ridge and associated fault that separated the Aqua Verde drainage from the lower Cienega Creek basin. This fault was interpreted to be a portion of the Santa Catalina Complex Fault System. The author noted that the fault could divert mountain-front recharge from the Rincon Mountains into Aqua Verde Creek, which connects with Cienega Creek near the western boundary of the preserve.

Ellett concluded that the source of perennial flow in the Cienega Creek Natural Preserve was the overflow of groundwater which was forced to the surface by shallow bedrock outcrops. Where the stream channel alluvium became thicker, the water seeped back into the subsurface and created a dry surface channel. These changes in the thickness of stream alluvial were thought to be controlled by the varying depths to bedrock in the area, which were also closely linked to the existence of faults.

The water temperature data collected by the author supported this model of changing stream channel alluvium thickness since there was a strong correlation between the changes in water temperature and the occurrence of geologic structures such as faults and bedrock outcrops. Since stream temperature data was collected in June, the surface water's temperature was considerably higher than the groundwater. Therefore, when a drop in surface water temperature was detected, it was concluded that groundwater was discharging at that point. This information, together with the gravity data, supported the idea that surface flow was dependent on aquifer thickness, which, in turn, was controlled by the depth and geometry of the bedrock.

12. *Progress Report on 1993-1994 Thesis Workshop Course, Hydrology 697A,B*
Department of Hydrology and Water Resources, University of Arizona
Prepared by the Thesis Workshop Committee
1994

This was a progress report on a University of Arizona, Department of Hydrology and Water Resource course that was developed to help students complete a Master's thesis in Hydrology and Water Resources. This program was directed at students who were interested in participating in a group project, or who were limited in their thesis research due to a lack of financial support. The overall project was defined by participating faculty members, and was split into different topic areas including the following departmental focal areas: surface water hydrology, subsurface hydrology, water chemistry, and water resources administration. The first year topic was a broad water resources evaluation of the upper Cienega Creek basin relative to various management issues. This was suggested by Julia Fonseca, Principal Hydrologist for Pima County Department of Transportation and Flood Control District, and Mike Block, former Hydrologist for Pima Association of Governments. Six students were chosen to participate in the program, and each student determined a topical area of interest to develop into a thesis.

This document consisted of one complete thesis done by the only undergraduate in the program, Beth Kurtz, who completed the thesis as partial fulfillment of her honors degree in Hydrology. The other five students participating in the program were graduate students, and at the time this progress report was submitted, none had fully completed their research. For that reason, progress reports on each individual's work at the date of publication were included. The content of the completed thesis is described in detail

below, and other participant's research are discussed individually, and are referenced separately under the complete title of the thesis. (See theses listed by the following authors: Damaris Chong-Diaz, Bill Ellett, and Howard Grahn.) However, the theses completed by Clayton Matt and Stephanie Ness were not available for review from the Department of Hydrology and Water Resources. Therefore, information included in their progress report is summarized below.

A) *Hydrologic Budget for the Cienega Creek Watershed*
Prepared by Beth Ann Kurtz as partial fulfillment of the requirements for the honors Bachelor degree in Hydrology, Department of Hydrology and Water Resources, University of Arizona
1994

This senior thesis focused on developing a preliminary water budget for the entire Cienega Creek watershed, which included both upper and lower basins. Due to project constraints, the standard water budget formulas were simplified. From calculated recharge amounts, it was suggested that enough recharge occurred during "wet" cycles to support perennial stream flow during short-term drought conditions. No further conclusions could be drawn due to limited data.

B) *Institutional Considerations in Water Resources Management of the Upper Cienega Creek Basin*
Prepared by Clayton Matt, Master's Thesis submitted to the Department of Hydrology and Water Resources, University of Arizona
1995

The purpose of this thesis was to examine the physical, legal, and institutional setting for the upper Cienega Creek basin from a water resource system perspective. Past and present water resource management policies were described. These, together with an understanding of the hydrologic processes which controlled the riparian area, were reviewed to determine which processes and policies were essential to the continued health of the riparian habitat. The thesis also discussed how the legal and institutional systems could be used to facilitate the long-term life of the riparian habitat under current management conditions, as well as under various future scenarios. Recommendations that could strengthen water management for Cienega Creek and could ensure the protection of the riparian habitat were presented.

C) *Time Series Analysis of Cienega Creek Perennial Flows*
by Stephanie Ness, Master's Thesis

This research entailed a time series analysis of 15 years of daily flow data provided by the Pima County Vail Station. From initial examination of the data, it was concluded that Cienega Creek's flow was highly variable like many streams in desert climates. Two wet and two dry periods were assumed. A best fit beta distribution of the flow data for the four recognized seasons was underway at the time of this progress report. When distributions that accurately reproduced the historical seasonal means, variances, and skews were found, the author planned to run the simulations over extended periods of time. From these simulations, probability statements would be made concerning future low and high flows which could be applied to future flood control planning, and maintenance of the riparian habitat.

13. *Hydrologic Availability and Use of Streamflows at the Cienega Creek Natural Preserve Pima County, Arizona*
Prepared for Arizona Department of Water Resources by Pima County Department of Transportation and Flood Control District
1993

The purpose of this report was to analyze and present data related to the in-stream flow application for Cienega Creek. Pima County Flood Control District (PCFCD) requested the in-stream flow water right to protect Cienega Creek from any potential diversion which could adversely affect the perennial flow, and to protect the wildlife dependent upon the stream for survival. In order to receive an in-stream flow permit from the Arizona Department of Water Resources (ADWR), PCFCD had to quantify the amount of water needed, and verify its availability during periods of beneficial use.

The beneficial-use-of-flow stated in this report was to support the needs of wildlife. The requested amounts of water were based on median flows registered by the U.S. Geological Survey at the Vail, Arizona station. The availability of flow was based on long-term streamflow measurements made by the Arizona Department of Environmental Quality (ADEQ) from 1987 to 1992, which greatly exceeded the one-year minimum data collection period mandated by ADWR. Included in Appendix A of this report is a chronology of events related to the Cienega Creek water rights action. Other appendices include precipitation data for the lower Cienega Creek watershed, statistical analyses of streamflow, and observed and unobserved wildlife of the Cienega Creek Natural Preserve.

14. *Unique Waters Final Nomination Report for Cienega Creek Natural Preserve Pima County, Arizona*
Prepared for the Arizona Department of Environmental Quality-Water Quality Standards Unit by Julia Fonseca (Pima County Department of Transportation and Flood Control District), Mike Block (Pima Association of Governments), Melinda Longsworth (Arizona Department of Environmental Quality) and Jim Boggs (Arizona Department of Environmental Quality)
1990

In this document, data supporting the designation of a portion of Cienega Creek as a Unique Water of the State of Arizona are presented. Unique Water status was determined to be crucial to Cienega Creek since it provides additional water quality protection through the use of only short-term waivers allowing for degradation of the surface water. In addition, surface waters designated as Unique Waters have more-stringent water quality standards than waters without this designation. In order to qualify for Unique Water status, a stream segment must meet one or more of the following criteria: (1) outstanding public resource classified so because of the surface water's associated flora, fauna, size, aesthetic value, wilderness characteristics, archaeology, or geology; (2) critical habitat for species of national or state significance; or (3) existing water quality that exceeds state surface water quality criteria, or that the economic and technical capability exists for the surface water to surpass the prescribed surface water quality criteria.

It was determined that Cienega Creek was an excellent candidate for this designation because its water quality was consistently better than state standards, and the area maintained rare habitats of ecological, recreational, and educational significance which would be of great value to metropolitan Tucson.

This document presented a sampling plan developed and implemented by Pima County Department of Transportation and Flood Control District (PCDOTFCD), Arizona Department of Environmental Quality (ADEQ), and Pima Association of Governments (PAG) personnel. Results from studies and data were listed and interpreted, including results from groundwater level, groundwater quality, and surface water quality research.

Further specific information relating to the Cienega Creek area was also included. For example, details about soils and geomorphology and potential sources of contamination were described.

Also included in this report was a Water Quality Management Plan for the nominated reach. The plan identified several local and state agencies from which action is required to manage the reach. Seven actions under local administration were listed. Two of the more significant actions were to include policies which prevent water quality degradation in new area, community, neighborhood, specific and zoning plans which replace the Vail-Posta Quemada Zoning Plan, and to develop revegetation standards for the purpose of mitigating sediment generation caused by construction, mining, and maintenance of utility and transportation corridors. Additional actions were listed under “State Administration,” “Monitoring,” and “Remediation.”

15. *Geophysical Surveys at the Avra Valley Test Site and Cienega Creek*
Prepared by the Laboratory for Advanced Subsurface Imaging, Department of Mining and Geological Engineering, University of Arizona
1993

This document reported the results of geophysical surveys which were conducted by University of Arizona students as part of their Geological Engineering/Geoscience 416/516 Geophysics Field Camp. TEM, IP-Resistivity, Seismic Refraction, and Gravity studies were completed at the Cienega Creek site in order to identify the depth to water and subsurface structure. Assorted maps, figures, data, and interpretation of results are included.

16. *Regional Overview of Land Acquisition in the Cienega Creek Watershed-Strategy, Benefits, and Opportunities*
Prepared by the Pima County Manager's Office and Pima County Department of Transportation and Flood Control District - Planning Division
1990

This report documented the regional significance of land purchases made from Houghton Rd. to the Santa Cruz/Pima County line, along the Pantano-Cienega riverine corridor. These land purchases were consistent with Pima County 's Comprehensive Plan dated September 1989, as well as the Open Space Plan developed in 1988. A continuous river park was included in both plans for all river courses in the Tucson basin, including the Pantano Wash. The Comprehensive Plan originally proposed that a river park extend along Pantano Wash from Houghton Rd. to slightly upstream of Colossal Cave Rd. near Vail. This area has now been designated the Pantano-Cienega corridor.

The Pantano-Cienega corridor was divided into five subareas depending upon past or current (as of August 1990) acquisition strategies. Each subarea's past acquisition of property, or intended future acquisition plans, were described in this document. In addition, the regional benefits gained from the acquisition of floodprone property were discussed. For instance, flood control and flood damage moderation, provision of a high quality water source, maintenance of the quantity of subsurface water recharging into the Tucson basin, establishment and expansion of open space, preservation of habitat and biological diversity, and preservation of prehistoric and historic sites within Pima County were all regional benefits obtained from the acquisition of floodprone land.

17. *Preliminary Management Analysis in Support of the Cienega Creek Unique Waters Nomination*
Prepared by Pima County Department of Transportation and Flood Control District
1988

This report documented the initial management analysis for establishing Cienega Creek as a Unique Water. Preliminary information regarding water quality characteristics, as well as land uses and management considerations, were discussed. Also included was limited surface water quality data from 1961, 1981, and 1987, and results from a groundwater sample analyzed in 1984. The following were included as appendices: (A)

map of the 1987 land status in the Cienega Creek watershed; (B) Historic Account of Grazing Intensity along Cienega Creek; (C) Declaration of Restrictions, Covenants and Conditions for the Cienega Creek Natural Preserve; (D) The Cienega Creek Natural Preserve Permit; (E) Empirita Ranch Area Plan; and (F) Coronado National Forest Plan Policies.

18. *Preliminary Report on the Hydrology of Cienega Creek Groundwater Basin*
Prepared by Michele Kennard, Allan E. Johnson, and Thomas W. Perry for Arizona Department of Water Resources, Division of Hydrology, Special Studies
1988

This document was a preliminary report on the hydrogeology of the Cienega Creek groundwater basin. Its purpose was to determine if sufficient information was available to complete a preliminary evaluation of the Cienega Creek Groundwater Basin for inclusion in the Tucson AMA. Included were descriptions of the four major hydrologic units in the basin: the younger alluvium, the basin fill alluvium, the Pantano Formation, and the bedrock complex. Also, predevelopment and current conditions were compared and contrasted, providing a unique perspective on the changes which occurred in the Cienega Creek basin since the 1880's. The report concluded that groundwater conditions in the basin had not been significantly altered due to development, although surface appearance of the basin had changed considerably in the last 100 years. Therefore, it was determined that Cienega Creek basin did not successfully meet the criteria needed to support a critical groundwater designation which would have allowed the basin to be incorporated into the Tucson AMA.

19. *Water Adequacy Report Stage One Development Empirita Ranch Area Pima County, Arizona*
Prepared by Errol L. Montgomery & Associates
1985

This report documented a hydrogeologic investigation conducted to evaluate the adequacy of groundwater supply for the proposed Stage One development of 6,600 residences at Empirita Ranch. Included were pumping tests results and construction information for exploratory wells. Water level measurements from 1984 for Empirita Ranch wells were listed, as well as a table of stream flow measurements taken at the Narrows by the University of Arizona Water Resources Research Center from 1975-1976, and an associated hydrograph for the years 1975-1982.

20. *Impact of Future Groundwater Development in Cienega Creek Area*
John Mark Boggs, Master's Thesis submitted to the Department of Hydrology and Water Resources, University of Arizona
1980

This thesis presented data and research compiled and analyzed to assess the potential impact of proposed pumping by the Anamax Mining Corp. in the Cienega Creek basin area. Previous investigations were cited, including a comprehensive hydrological investigation completed prior to 1980 by Harshbarger & Associates (1978). Data from 13 pumping tests, conducted in the central basin during the late 1970's for Anamax Mining Corp., were used to establish hydrologic and geologic conditions for the applied models. In addition, precipitation data were analyzed in order to complete a simple water budget for the Cienega basin. The author referenced Kafri et al. (1976) for precipitation data and isohyetal contours, which were extrapolated from precipitation records. The precipitation model by Duckstein, Fogel, & Thames (1973) was used to adjust precipitation values, assuming that rainfall varied with topographic elevation.

The Water Resource Research Center provided groundwater level records for three wells in the area, in addition to surface water measurements taken at the Narrows from 2/75 to 12/76. Average baseflow at the Narrows was estimated to be 1.8 cubic-feet per second (cfs) or 1300 acre-feet per year (af/yr.). However, it was stated that the flow measurements were taken during a "dry" year. Geraghty & Miller (1970) estimated average baseflow to be at 2.0 cfs or 1400 af/yr. In relation to groundwater recharge, the author cited studies done by Kafri & Ben-Asher (1978). They concluded that essentially all rains falling on soils greater than 20 cm in thickness return to the atmosphere by evapotranspiration, except for those at lowland margins bordering mountains which are coarser-grained sediments, and therefore increased infiltration.

The author estimated from his lowland model that basin recharge was approximately 10,100 af/yr. Of this total recharge, 45% was generated from the Whetstone Mountains, 22% from the Santa Rita Mountains, 20% from the Empire Mountains, 7% from the Canelo Hills, and 6% from the Mustang Mountains. From a completed sensitivity analysis of the calibrated basin model, the author suggested that groundwater levels were most sensitive to changes in transmissivity (or associated errors in determining transmissivity) in areas of high natural specific discharge, or in areas of future pumping. It was further concluded that the Cienega Creek baseflow would progressively decrease during pumping periods, and surface flow would cease entirely after 15 years of pumping at the rate of 10,000 to 14,000 af/yr.

21. *Southern Pacific Transportation Company Cienega Creek Natural Preserve Hazardous Material Emergency Response Plan*
Southern Pacific Transportation Company
Not Dated

This plan addressed the management of hazardous materials incidents where Southern Pacific Transportation Company (SPTC) property borders on the Cienega Creek Natural Preserve. The plan included instructions to train crew employees, instructions to the Western Region Transportation Center, and details regarding effects of certain railroad activities. Names and telephone numbers of local contacts were listed under reporting requirements; these included the local fire department, the local law enforcement agency, Pima County Department of

Environmental Quality, and many others. Several specific requirements related to maintenance activities were also identified. The plan must be reviewed yearly and updated as necessary by the Senior Division Manager.

22. *USGS Water Resources Data for Arizona*
    Annual reports

The USGS publishes annual reports summarizing water resources data for Arizona. Discharge data for the Vail gage at Del Lago dam are included in these reports.

23. *Empirita Ranch Hydrogeologic Monitor Program*
    Errol L. Montgomery and Associates
    Annual Reports, 1984 - 1993

These reports summarize the results of groundwater and surface water monitoring in lower Cienega basin. Groundwater level data, water quality data, and extent of streamflow are reported.

# X. CONCLUSIONS AND RECOMMENDATIONS

PAG collected a large amount of data and reviewed numerous studies for this report. From this information, several conclusions can be drawn:

- Cienega Creek is an important natural resource for Pima County and Arizona. The importance of Cienega Creek is evidenced by Pima County's acquisition of adjacent lands and establishment of the Cienega Creek Natural Preserve; by the State of Arizona's designation of the creek as a Unique Water and issuance of an in-stream flow right; and by the numerous scientific studies that have been completed by the University of Arizona and other organizations.

- Groundwater levels near lower Cienega Creek are typically less than 30 feet below land surface at several of the wells included in PAG's monitoring program. Water levels declined roughly 15 feet in the upper reaches of the preserve between 1984 and 1997. This was probably due to a transition from unusually wet conditions in the early 1980s to significantly drier conditions in the late 1980s and 1990s. Water levels in the central part of the preserve were stable, presumably as a result of greater subsurface storage.

- Groundwater levels typically respond to precipitation trends within one month. Water levels at most wells show consistent seasonal trends, although several anomalous trends have occurred at individual wells. Seasonal variations in water levels of up to 10 feet have been recorded.

- Groundwater in the preserve flows from the mountains toward the creek, and along the creek to the northwest.

- Perennial flow is present at numerous locations along lower Cienega Creek, and perennial flow has been maintained through a range of climatic conditions, including a significant drought. Flow rates and the extent of continuous surface flow have shown significant seasonal and interannual variation. In the summer of 1996, when drought conditions developed, some reaches that previously flowed year-round began to go dry; these reaches included the Tilted Beds site and the SP 1006 reach along Cienega Creek.

- Streamflow typically responds to precipitation trends within one month, although the response has been somewhat variable.

- Streamflow in lower Cienega Creek is closely linked to conditions in the local aquifer. However, the correlation between streamflow data for a particular reach and groundwater data for a particular well tends to diminish substantially with increasing distance, especially if significant bedrock highs are present between the sites. Streamflow appears to be more-closely linked to water levels in wells drilled into the alluvial aquifer than to water levels in wells drilled into the Pantano formation or other bedrock formations.

- Diurnal variations in groundwater levels of about 0.3 feet occur at the Cienega well in June. A rough estimate of the total maximum evapotranspiration (ET) rate of 3.35 cfs was calculated from this diurnal variation. Significant diurnal variations do not typically occur at the Cienega well in March, or at the Del Lago #1 well at any time of the year.

- Significant diurnal variations in stream discharge occur in the summer due to ET. ET losses of up to 0.6 cfs were recorded in Cienega Creek in June. ET losses in stream discharge did not occur at other times of the year.

- A University of Arizona groundwater flow model of the lower Cienega basin predicts that impacts from groundwater withdrawals of 1,600 af/yr. (2.2 cfs) from the Empirita Ranch development could be severe. PAG's monitoring program appears to be adequate to detect these impacts. It would be useful, however, to reinstate the streamflow observations near the Cienega well.

The following recommendations are submitted for consideration:

- Monthly monitoring of groundwater levels, streamflow extent and stream discharge in the preserve should continue, so that long-term trends can be firmly established, and steady-state conditions firmly documented. Streamflow observations at the Cienega well site should be reinstated. An annual survey of streamflow extent along the entire reach of Cienega Creek from Jungle Road to the Del Lago dam would also be useful. This survey should be conducted during late June or early July, when streamflow is typically at its lowest. The annual survey could either supplement or replace the current streamflow extent monitoring program, depending on the available budget and on the staff time required to complete it.

- Additional diurnal measurements at the Cienega well and other wells should be conducted to develop a more reliable estimate of ET. The measurements should each encompass a 24-hour period. At least one measurement should be conducted between March and June, and at least one should be conducted between June and December. The estimated area of riparian woodlands should be updated with more recent aerial photographs and incorporated into the ET calculations.

- The Chong-Diaz model should be thoroughly reviewed and updated to include revised estimates of ET, additional information on subsurface geology, and the effects of ephemeral stream recharge.

- If future models with updated input parameters confirm the Chong-Diaz model results, any plans for long-term groundwater withdrawals at a scale of 1,600 af/yr. should be reconsidered.

# XI. REFERENCES


Anderson, T. W., 1985. *Hydrologic Setting, Objectives, and Approach of the Southwest Alluvial Basins, RASA Study* in *Regional Aquifer Systems of the United States Southwest Alluvial Basins of Arizona*, AWRA Monograph Series No. 7, American Water Resources Association, T. W. Anderson and A. Ivan Johnson, eds.

Arizona Department of Environmental Quality, 1996. *Arizona Water Quality Assessment.*

Arizona Department of Water Resources, 1988. P*reliminary Report on the Hydrology of Cienega Creek Groundwater Basin.*

ASARCO, 1995. *The Rosemont Ranch Land Exchange.*

Chong-Diaz, D., 1995. *Modeling of Stream Aquifer Interaction in Lower Cienega Creek Basin using a Finite Element Technique.* Master of Science Thesis, University of Arizona, Tucson, Arizona.

Ellett, W.J., 1994. *Geologic Controls on the Occurrence and Movement of Water in the Lower Cienega Creek Basin.* Master of Science Thesis, University of Arizona, Tucson, Arizona.

Errol L. Montgomery and Associates, Inc., 1993. *Hydrogeologic Monitor Program, Calendar Year 1992, Empirita Ranch, Inc., Pima and Cochise Counties, Arizona.*

Errol L. Montgomery and Associates, Inc., 1985. *Water Adequacy Report, Stage One Development, Empirita Ranch Area, Pima County, Arizona.*

Fonseca, J., 1996. Interoffice transmittal containing a copy of a site plan for a proposed mine in the Santa Rita Mountains.

Fonseca, J., Block, M., Longsworth, M., and J. Boggs, 1990. *Unique Waters Final Nomination Report for Cienega Creek Natural Preserve, Pima County, Arizona.* Prepared for Arizona Department of Environmental Quality Water Quality Standards Unit.

Freeze, R. A., and J. A. Cherry, 1979. *Groundwater.* Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Gatewood, J.S., Robinson, T.W., Colby, B.R., Hem, J.D., and L.C. Halpenny, 1950. *Use of Water by Bottom-land Vegetation in Lower Safford Valley, Arizona.* U.S. Geological Survey Water-Supply Paper #659.

Grahn, H. L., 1995. *A Hydrogeochemical Evaluation of the Lower Cienega Creek Subbasin, Pima County, Arizona.* Master of Science Thesis, University of Arizona, Tucson, Arizona.

Harshbarger and Associates, Inc., 1975. *Analysis of Groundwater Development Program in the Empire Ranch Area: Preliminary Draft.*

Kennard, M., Johnson, A. E., and T. W. Perry, 1988. *Preliminary Report on the Hydrology of Cienega Creek Groundwater Basin.* Arizona Department of Water Resources Division of Hydrology Special Studies.

Kulakowski, L., and B. Tellman, 1990. *Instream Flow Rights: A Strategy to Protect Arizona's Streams.* Issue Paper Number Six, Water Resources Research Center, University of Arizona, Tucson, Arizona.

Lawson, L., 1997. Personal communication with ADEQ staff, 12/8/97.

Maddock, T., 1998. Personal communication 1/26/98.

McGann & Associates, 1994. *Cienega Creek Natural Preserve Management Plan and Background Report.* Prepared for Pima County Department of Transportation and Flood Control District.

Meyboom, P., 1967. *Groundwater studies in the Assiniboine River Drainage Basin: II. Hydrologic characteristics of phreatophytic vegetation in south-central Saskatchewan.* Geol. Surv. Can. Bull 139, 64 pp.

National Oceanic and Atmospheric Administration, 1995. *Local Climatological Data, Annual Summary with Comparative Data, Tucson, Arizona.*

National Climate Data Center, 1997. Palmer Drought Indices from World Wide Web (http://www.ncdc.noaa.gov/onlineprod/drought/temp/drought_6843.txt)

Palmer, 1965. Meteorological Drought Research Paper #45, US Weather Bureau, Washington, DC.

Pima Association of Governments, 1996. *Cienega Creek Natural Preserve Surface Water and Groundwater Monitoring Project, Quarterly Report, January - March 1996.*

Pima Association of Governments, 1996a. Minutes of February 2, 1996, meeting of the Environmental Planning Advisory Committee.

Pima County Department of Transportation and Flood Control District, 1990. *Regional Overview of Land Acquisition in the Cienega Creek Water shed- Strategy, Benefits, and Opportunities.* Prepared for Pima County Board of Supervisors and Pima County Flood Control District Board of Directors.

Pima County Department of Transportation and Flood Control District, 1993. *Hydrologic Availability and Use of Streamflows at the Cienega Creek Natural Preserve, Pima County, Arizona.* Prepared for an in-stream flow permit from Arizona Department of Water Resources (Application No. 33-89090).

Pima County Development Services Department, 1996. *Pima County Comprehensive Plan.* Revised December 1996.

Pool, D. R., 1985. *Aquifer Geology of Alluvial Basins of Arizona.* in *Regional Aquifer Systems of the United States Southwest Alluvial Basins of Arizona,* AWRA Monograph Series NO. 7, American Water Resources Association, T. W. Anderson and A. Ivan Johnson, eds.

Richard, S. M., 1996. Personal communication with Arizona Geological Survey staff, August 14, 1997.

Richard, S. M., and R. C. Harris, 1996. *Geology and Geophysics of the Cienega Basin Area, Pima and Cochise Counties, Arizona.* Final Report to the Arizona Department of Water Resources, Water Protection Fund Grant 95-016WPF. Open-file report published by the Arizona Geological Survey, Tucson, Arizona.

Roudebush, E. M., 1996. *The Influence of Bedrock on Perennial Streamflow in the Upper Cienega Creek Basin, Pima County, Arizona.* Master of Science Thesis, University of Arizona, Tucson, Arizona.

Sen, O. L., 1996. *Atmospheric Exchanges of Riparian Vegetation in a Semi-Arid Environment.* Master of Science Thesis. University of Arizona, Tucson, Arizona.

Shuttleworth, W. J., Unland, H.E., Arain, A.M., Harlow, C., Houser, P.R., Garatuza-Payan, J., Scott, P., and O. L. Sen, 1997. *Evapotranspiration from a Riparian Habitat in a Semi-arid Environment.* Department of Hydrology and Water Resources study, University of Arizona, Tucson, Arizona.

Todd, D. K., 1980. *Groundwater Hydrology*, 2nd ed., John Wiley & Sons, Inc.

United States Geological Survey, 1996. Water Resources Data, Water Year 1996. Station Number 09484600, Pantano Wash Near Vail, Arizona.

White, W. N., 1932. A *method of estimating groundwater supplies based on discharge by plants and evaporation from soil,* U. S. Geological Survey Water-Supply Paper 659.

Williams, M.D., 1996. *Evapotranspiration in Southeast Arizona Semi-arid Watersheds: Walnut Gulch and Cienega Creek.* Master of Science Thesis, University of Arizona, Tucson, Arizona.

Zimmerman, R. L., 1969. *Plant ecology of an arid basin, Tres Alamos-Redington Area.* United States Geological Survey Professional Paper 485-D: 1-51.