MEMORANDUM

Date: August 13, 2013

To: The Honorable Chairman and Members
Pima County Board of Supervisors

From: C.H. Huckelberry
County Administrator

Re: **Discussions between the U.S. Army Corps of Engineers, the Regional Flood Control District and the Tucson Audubon Society Regarding an In-lieu Fee Mitigation Site for Cienega Creek as It Relates to Mitigating Impacts to Waters of the United States by the Proposed Rosemont Copper Mine**

Discussions have occurred between Regional Flood Control District (RFCD) staff and the Tucson Audubon Society (TAS) with the U.S. Army Corps of Engineers to create an in-lieu fee mitigation project in the Cienega Creek to offset impacts to Waters of the United States caused by the Rosemont Copper mining proposal.

The attached July 31, 2013 letter discusses County and TAS concerns over such a proposal, mainly due to the lack of a dependable wet water supply to provide the mitigation, regardless of the number of surface water rights being acquired and potentially transferred by Rosemont.

Acquisition of these surface water rights to protect surface water flows in the Cienega Creek is desirable. Acquiring the Pantano Dam site and ending surface water diversions to the Del Lago Golf Course is also desirable, as is the acquisition of an extraction well owned by Vail Water Company that is near the Dam.

However, the RFCD and TAS cannot assume full legal responsibility for the required reestablishment of specific acreage of riparian vegetation downstream of the dam site. Little is known about the subsurface soil conditions and the ability to raise the groundwater level below the property owned by the RFCD along the Cienega Creek downstream of the dam site by the reintroduction of surface waters into this stream reach. Reestablishment of sustainable riparian vegetation, and the acreage of same, is highly dependent on how far stream flow will travel downstream of the dam before infiltrating, how dependable the supply of water from regular surface flow, and whether shallow groundwater level could be provide for obligate riparian vegetation.

In addition to the July 31, 2013 letter, I have attached a report prepared by Mr. Brian Powell of our Sustainability and Conservation Office entitled *Water Resource Trends in the*

Cienega Creek Natural Preserve, Pima County, Arizona, August 2013, for your information and review.

CHH/dph

Attachments

c: John Bernal, Deputy County Administrator for Public Works
Suzanne Shields, Director, Regional Flood Control District
Julia Fonseca, Environmental Planning Manager, Conservation and Sustainability
Nicole Fyffe, Executive Assistant to the County Administrator

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In – Lieu Fee Mitigation Program

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Dr. Paul Green
Executive Director

July 31, 2013

Ms. Marjorie Blaine
U. S. Army Corps of Engineers
5205 E. Comanche Street
Davis-Monthan AFB, Arizona 85707

Subject: Potential In-Lieu Fee Mitigation Site for Cienega Creek

Dear Ms. Blaine:

This letter follows our June 19, 2013 presentation and meeting with you and the EPA concerning the feasibility of developing an In-Lieu Fee (ILF) Mitigation site along Cienega Creek downstream of the Pantano Dam in accordance with Section 404 of the Clean Water Act. As you know, the District/Audubon conceptual design for developing this ILF Mitigation site is completely dependent on the long-term availability of "wet water" in order to be able to mitigate "like-for-like" for impacts to perennial and intermittent sources of "wet water" such as streams, seeps, and springs within the watershed.

The plan for the Cienega Creek ILF Mitigation site is currently at the concept level and we have not yet had an opportunity to fully evaluate detailed water requirements or the level of restoration that would be feasible and sustainable. It is critical that any design and performance standards that we develop be flexible given the uncertainty in water availability, intensity of flooding, and other site characteristics which are beyond our control as Program Sponsors. Based on our due diligence to date, we have concluded that significant uncertainty exists regarding our ability to mitigate for streams, seeps, and springs based on approximately 20 years of data documenting progressively declining surface water within Cienega Creek and questions regarding legal access to the surface water. These issues will determine the volume of water physically and legally available to develop a sustainable ILF Mitigation site along Cienega Creek.

Focus: Measurements of Base Flow and Prospects for Habitat Restoration
As we assess the viability of a proposed ILF mitigation project at this site, we call your attention to the recent United States Geological Survey (USGS) measurements of base flow which indicate that the total available wet water at the Pantano Dam is only an average of 360 Acre Feet per Year (AFY) (see exhibits). Even if all water rights at the Pantano Dam were available

to the project, 360 AFY is the actual volume that might be reasonably assumed to be available for mitigation and restoration. This limited base flow is insufficient to implement 22 acres of effective stream restoration with obligate hydro-riparian species, as are found upstream of the dam along perennial and intermittent streams, seeps and springs.

We estimate that approximately 700 AFY are needed to sustainably raise the groundwater level downstream of the dam to a level that would support hydro-riparian species without continued surface irrigation. The current base flow is insufficient and may actually decrease if the downward trend in surface water quantity continues. Ongoing irrigation is not a sustainable strategy for the long-term survival of hydro-riparian species nor does it meet the conditions of the 2008 404 Mitigation Rule. Use of xero-riparian species might increase the long-term chances of project success, but some xero-riparian species do not tolerate regular flooding and could die, leaving primarily ruderal annuals and short-lived perennials.

Restoration and enhancement of overbank xero-riparian vegetation would also require some level of irrigation for an establishment period of five to seven years. The amount of overbank mitigation possible may have to be reduced significantly from our conceptual estimate of 178 AFY if wet water availability continues to diminish.

In our presentation on June 19th, we stressed that the availability of wet water is THE limiting factor in determining the quantity and quality of potential mitigation that might be provided at this site. The availability of wet water also dictates how we would need to stage the implementation of restoration in channel as well as in the overbank. We would need to manage and control ALL of the available wet water, in a timely fashion, to most effectively irrigate those areas and maximize our rate of vegetation establishment within the proscriptions of the 2008 404 Mitigation Rule.

The diminishing base flows in Cienega Creek, from studies conducted for over 20 years and most recently by the Pima Association of Governments, is a trend that is expected to continue into the future. It is possible that, under the best of circumstances, there may only be enough surface flow to maintain the existing riparian vegetation upstream of the dam in the future, if that.

The wetted length of the Cienega Creek continues to decrease, closely mirroring the trend of the surface water quantities observed at the dam (see exhibits). While there are seasonal and event-based variations in flow, a significant observable decline in flow at the Pantano Dam has been documented over the past 20 years; it would therefore be prudent to assume a continued decline in base flow as we design any potential ILF Mitigation site.

Water Rights

Legally, the right to use the surface water flows at the Pantano Dam are tied to three water rights: one from 1908 for 597.755 AFY, one from 1933 for 477.545 AFY and a 1935 right for 46.455 AFY. All these water rights are currently held by the owner of Del Lago Golf LLC. We understand that the Applicant has indicated that they have an option to acquire these water rights.

We have recently received three draft Letters of Intent (LOI) from the Applicant's consultants, WestLand Resources, that outline the concepts for possible commitments of water and water rights which they propose to apply to the potential Cienega Creek ILF Mitigation site. Enclosed are these three letters, and their Pantano Creek Water Allocation Summary, which can be summarized as follows:

- A pilot project to begin release of wet water below the Pantano Dam in the late first or early second quarter of 2014 and continue through 2014 (up to the maximum of 46 AFY (1935 right). This would continue through calendar year 2015 (up to an additional 46 AFY). At the end of the project, it is proposed that District/Audubon and the Applicant will cooperate to develop a final analysis of the results of the pilot project.

- Transfer of water rights for only 413 AFY specifically committed to the potential Cienega Creek ILF Mitigation site, all of which will come from the 1908 priority right to be acquired by the Applicant.

- The Applicant would retain 184.755 AFY of the 1908 water right, and 227.545 AFY of the 1933 right which would go into a Managed Underground Storage Facility (MUSF), located generally in the area between Pantano Dam and Colossal Cave Road.

While the pilot project wet water is not identified as being dedicated to, or a part of, the ILF Program, we note that the 46.455 AFY from the 1935 right has not been available for some years and question if it will be available in 2014 or 2015. We also wonder if and how the MUSF can be co-located with the ILF Mitigation site and what would happen if there is less wet water than anticipated – how would the 1908 Water Right wet water be split and applied between the MUSF and the ILF Project? What would be the impact(s) of the Applicant's proposed recovery well on the groundwater levels essential to the potential ILF Mitigation site?

District/Audubon ILF Program Requirements for a Viable Cienega Creek Mitigation Site
Key components that can be controlled and that are therefore required for establishment of a Cienega Creek ILF Mitigation site include:

- Water Rights Transfer: All of the water rights, for which the Applicant has reportedly acquired a purchase option, should be severed and transferred to the District/Audubon ILF Program and restricted for use of the Cienega Creek ILF Mitigation site. Additional storm water flows would benefit the ILF Mitigation site but not be credited to the ILF or elsewhere.

- MUSF: An agreement that water loss from evaporation and transpiration attributable to the proposed Managed Underground Storage Facility will not count towards the water used by ILF restoration.

- Vail Water Company Well Site: The existing well at the Pantano Dam has a pump capacity of 840 gallons per minute. The well site needs to be acquired by the Applicant and ownership passed to the District. The well will have a conservation easement

restricting use to prevent further reduction in stream flow and groundwater levels that would occur if this well was ever utilized for residential water supply. It may be used for monitoring.

- Certainty on Maintenance of Dam/Infrastructure: At minimum, an easement will be needed to provide for maintenance of the dam, spillway, pipeline, inlet, and 2 acre in holding. Outright ownership of, and additional funding for, those assets would be preferable, as the ILF Sponsors specifically do not wish to assume liability for the 100 + year old structure and associated facilities without such assurances.

- ILF Performance Standards: Flexibility on ILF performance standards and the implementation schedule will be necessary due to factors that are beyond our control:

    - Uncertainty regarding the subsurface geology which impacts both sustainable groundwater levels and the distance downstream of the dam where water may flow in stream.
    - Uncertainty regarding the base flow across and into the ILF Mitigation site.
    - Uncertainty regarding the intensity of future flooding.
    - Uncertainty regarding the area groundwater due to upstream disturbance and changes to groundwater in the watershed.
    - Obligation for Del Lago Golf LLC to continue to receive surface water. Thus, any release of water would need to be planned in incremental stages.
    - Timing uncertainty on the construction of the Vail Water Company pipeline to service the Del Lago golf course.
    - Supplemental Funding for Monitoring and Maintenance activities.
      While the LOIs we have received from WestLand articulate some progress in resolving some issues, there remains much more work to be done to further reduce the uncertainties, as described in this letter.

BACKGROUND

Climate Change, Drought, and Available Water

It is widely accepted that the Sonoran ecoregion is currently in the throes of a profound drought and that these types of drought have occurred historically in the region. On June 23, 1999, the Arizona Division of Emergency Management declared a statewide Drought Emergency Declaration (PCA99006) which remains in effect as a "current open disaster". A Drought Declaration for the State (Executive Order 2007-10) was issued in May of 2007. The Governor's Drought Interagency Coordinating Group has recommended, as recently as May 20, 2013, continuing both declarations based on projections of warmer temperatures and increased wildfire risk. All counties in Arizona currently have a disaster designation from the US Department of Agriculture due to impacts of ongoing drought, high winds, and wildfires. http://www.azwater.gov/AzDWR/StatewidePlanning/Drought/ICG.htm.

New findings appear to indicate that the ongoing drought may be exacerbated beyond the negative impacts of previous climate patterns. Extreme drought conditions are likely to become more common. University of Arizona (U of A) climate models document current, and predict future, above average warming trends in the Sonoran Desert ecoregion which may exacerbate the extremes of previous precipitation patterns. Jonathon Overpeck, co-director of the U of A's Institute for the Study of Planet Earth, stated, "The climate in the Southwest is changing faster than anywhere else in the U.S." "The implications of climate change have already started in Arizona. We'll have to deal with warmer temperatures, less precipitation and more drought..." "These temperature changes that are coming are huge, will demand a lot of water and will make the droughts of the past look pale because they will be so much hotter," he testified before a US House of Representatives Science and Technology Committee hearing on water supply challenges for the 21st century (AZ Daily Star 5/15/2008).

Published May 2008, the *Synthesis and Assessment Product 4.3 (SAP 4.3): The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States* (http://www.sap43.ucar.edu/) is one of the most extensive examinations of the potential impacts of climate change on important US ecosystems undertaken to date. It concludes that, in arid region ecosystems that have not co-evolved with a fire cycle, the probability of loss of iconic, charismatic mega flora such as saguaro cacti and Joshua trees will greatly increase and that:

- Climate change is already affecting US water resources, agriculture, land resources, and biodiversity, and will continue to do so.

- Forests in the interior West, the Southwest, and Alaska are already being affected by climate change with increases in the size and frequency of forest fires, insect outbreaks and tree mortality. These changes are expected to continue.

- While much of the US has experienced higher precipitation and stream flow over the 20th century, the West and Southwest are notable exceptions. Increased drought conditions have occurred in these regions.

- There is a trend toward reduced mountain snowpack and earlier spring snowmelt runoff in the Western US.

- Weeds grow more rapidly under elevated atmospheric CO2. Under projections reported in the assessment, weeds migrate northward and are less sensitive to herbicide applications.

- Invasion by exotic grass species into arid lands will result, causing an increase fire frequency. Rivers and riparian systems in arid lands will be negatively impacted.

Regional models predict a 10% to 20% reduction in precipitation in the Southwestern US and northern Mexico in the next 75 years (Christensen *et al.* 2007), with most reductions in precipitation during winter months when circulation patterns over the Pacific Ocean prevent

moisture from entering the region through a movement of the storm track to the north (Powell, *Inventory and Status of Unsupplemented and Perennial Surface Water on Pima County Open-space Properties*, 2011).

Seager examined a total of 49 individual projections conducted with 19 climate models and found, even as early as the 2021–2040 period, only three projections show a shift to a wetter climate. In the multi-model ensemble mean, there is a transition to a sustained drier climate that begins in the late 20th and early 21st centuries in the southwestern US and parts of northern Mexico. In general, the American Southwest experiences a severe drying.

Seager explains this drying is unlike any climate state we have seen in the instrumental record. It is also distinct from the multi-decadal mega-droughts that afflicted the American Southwest during Medieval times. The most severe future droughts will still occur during persistent La Niña events, but they will be worse than any since the Medieval period, because the La Niña conditions will be perturbing a base state that is drier than any state experienced recently (Seager *et al.* 2007, Science, 25 May 2007, Vol. 316, pp. 1181-1184).

Overall, experts predict that the climate of Pima County will be hotter and dryer with more extreme periods of high temperatures and extreme weather events. To make things worse, higher average temperatures will have the effect of lowering effective rainfall because of greater evaporation and evapotranspiration. Recent work by The Nature Conservancy indicates that moisture stress (annual evaporation minus precipitation) on plants from 1970 – 2006 led to an effective decrease in precipitation of approximately 1/3 inches over much of Pima County (Rob Marshall, unpublished data) (Powell 2011).

Pima County has been in drought conditions for some time resulting in declining base flows in Cienega Creek (see enclosed graph). The USGS measurements of base flow in recent years indicate that the available wet water at the Pantano Dam is only about 360 AFY. This pattern of reduced available wet water at the Pantano Dam is expected to continue and is critical to the feasibility of our proposed Cienega Creek ILF Mitigation site and is beyond our control.

SUMMARY

The essential points indicate that it is distinctly possible that insufficient wet water is available for our proposed project in real and in legal terms:

- The proposed Cienega Creek ILF Mitigation site would require a minimum of 700 AFY of wet water to establish meaningful habitat restoration.

  The Applicant has an option to acquire the right to purchase approximately 1,122 AFY of surface water rights held by the Del Lago Golf Course to enhance aquatic habitat values in the Cienega Creek watershed.

- The acquirable rights are: 1908 Right of 597.755 AFY, 1933 Right of 477.545 AFY, and 1935 Right of 46.455 AFY.

- USGS measurements of base flow in recent years indicate that the available wet water at the Pantano Dam is only about 360 AFY and declining.

- Additional storm or flood flows do occur on occasion but those flows are completely unpredictable. The ILF cannot capture or utilize these flows without storage facilities. Also, such flood flows only provide a transitory rise in the groundwater levels.

- Ergo, no dependable wet water exists for 40% of the 1908 water right, and perhaps none at all for the 1933 and 1935 water rights; nevertheless,

    - The Applicant intends to transfer only 413 AFY of the 597.755 AFY 1908 water rights to the potential Cienega Creek ILF Project, far short of the identified minimum amount necessary for our proposed project.
    - The Applicant simultaneously intends approximately 825 AFY will be used for aquifer recharge via a managed underground storage facility (MUSF) below Pantano Dam, after the golf course has obtained another source of water for irrigation.
    - The Applicant anticipates that the District/Audubon ILF Program may develop a project that relies upon the waters discharged to the MUSF in excess of the benefits expected to support the Applicant's CWA Section 404 mitigation requirements.

- The District/Audubon ILF Program is concerned that the potential transfer of the water rights may be delayed until January 1, 2016 at the earliest. It is anticipated that it will take a minimum of two years for the Arizona Department of Water Resources (ADWR) to review and approve the application to sever 250 acre-feet of the 1933 water right and all of the 1935 water right and transfer the place of diversion and beneficial use to the Cienega Creek watershed. It is possible that irrigation districts and other water rights holders will object to the severance and transfer application, which could cause ADWR to deny the application. This adds considerable uncertainty to the viability of the proposed Cienega Creek ILF Mitigation site.

We reiterate that as we continue to study this site and attempt to plan a potential ILF Project, the dramatic nature of the base water flow decreases and associated uncertainties for future surface water flows, factors completely beyond our control, have become much more evident and relevant.

If we are to continue to proceed with planning for a Cienega Creek ILF Mitigation site, it will be critical that the Corps includes flexibility in developing mitigation site performance standards, with incremental implementation in direct accordance with wet water availability, and that the necessity for implementation of adaptive management at this site be stipulated in advance.

Nonetheless, at this point in time, the uncertainties attached to the long-term provision of wet water to this site lead us to question its viability.

We appreciate your understanding of the complex issues associated with the feasibility of developing a potential ILF mitigation site at Cienega Creek and appreciate your cooperation in facilitating the elements necessary, if you wish for us to continue to proceed with the development of a potential site plan. To that end, and for clarity of communication, we respectfully request that any and all future communication regarding this issue be conducted through and with you and only you.

Please do not hesitate to contact us should you have questions or concerns.

Sincerely,

Suzanne Shields, P.E.
Director and Chief Engineer
Regional Flood Control District

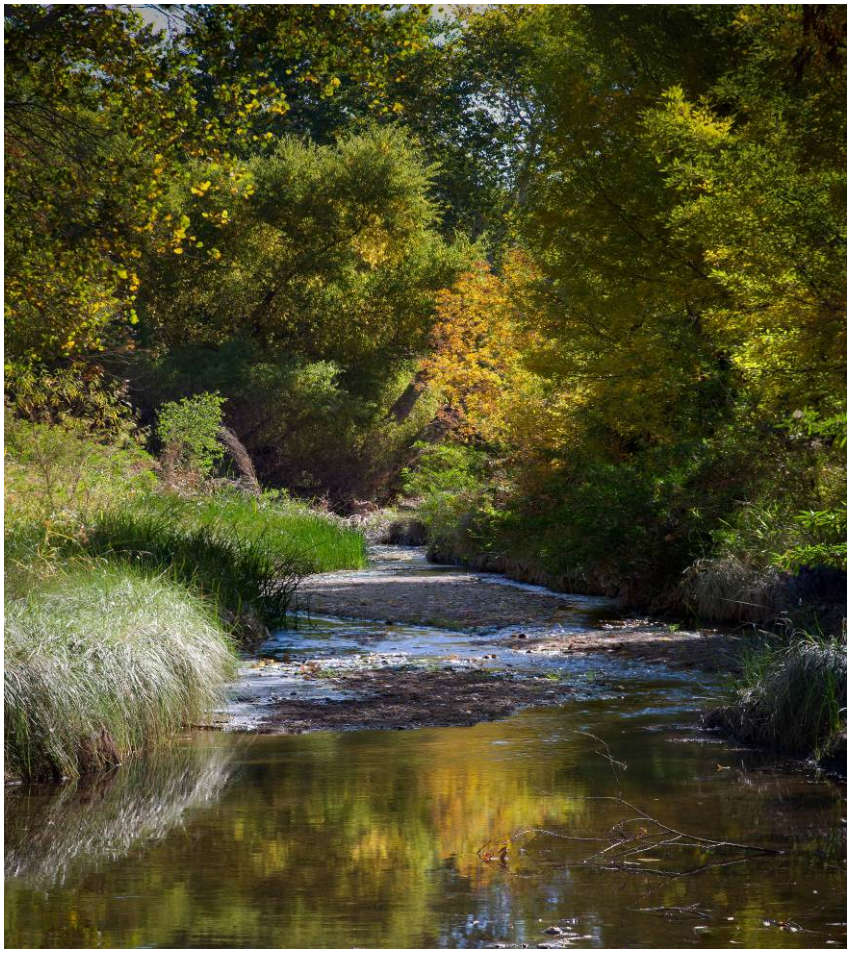
Dr. Green
Executive Director
Tucson Audubon Society

SS/PG/tj

Enclosures

c: Elizabeth Goldmann, Environmental Protection Agency

Water Resource Trends in the Cienega Creek Natural Preserve, Pima County, Arizona



August 2013

Brian Powell
Pima County Office of Sustainability and Conservation

Suggested Citation: Powell, B. F. 2013. Water resource trends in the Cienega Creek Natural Preserve, Pima County, Arizona. An unpublished report to the Pima County Flood Control District, Tucson, AZ.

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Executive Summary

The Cienega Creek Natural Preserve is the "crown jewel" of the County's extensive land holdings for natural resource conservation. The Preserve contains some of the region's most important aquatic and riparian habitat and is home to a number of threatened and endangered species. Because of its regional importance, and in consideration of the importance of water in maintaining and promoting the aquatic and riparian habitat, Pima County began monitoring water resources soon after the establishment of the Preserve in the 1980s. Since that time a number of monitoring efforts have resulted in a wealth of water-related data from the preserve, including data on precipitation, streamflow volume, extent of surface flow, and depth to groundwater. Though data have been collected and reported in annual reports and periodic assessments, there has not been a recent effort to thoroughly analyze these data or to use statistics to investigate the significance of the observed trends. This report addresses this need and does so using data collected principally from 1990-2011.

With the exception of precipitation, all water resources analyzed have shown declines since monitoring efforts began. In most cases, these declines have been both statistically and ecologically significant. Between 1990 and 2011, streamflow discharge (a measure of surface water volume) declined by 83%. Similarly, streamflow extent (i.e., the length of stream channel with surface water) declined by 88%. For many of the parameters, the hot, dry period prior to the monsoons was a period of extreme decline, such as for streamflow discharge, which declined by 97% when comparing June 1990 to June 2011 (Pantano Wash gage). Depth to groundwater, which is measured in a number of monitoring wells, declined less than other measures, yet declines were as much as 44%.

The causes for the observed declines are not entirely known because many factors are likely acting in concert. First, drought conditions were in place for much of the time period covered by the report; in some years precipitation was as little as 50% of normal. To compound the effects of the drought, there has seen a sharp rise in the number of new groundwater wells drilled for domestic and commercial use. In addition to these factors is the amount of water being withdrawn from the system by way of evapotranspiration, as well as the underlying hydrological and physical characteristics of the aquifer.

Water is the ingredient that makes the Cienega Creek Natural Preserve so special, yet water will become even more vulnerable in the future. Chief among the threats to water is a climate, which will be hotter and most likely drier. Development pressure will continue to impact the Preserve by way of more groundwater wells that take water from the natural system. The proposed Rosemont Mine will also impact water resources in Davidson Canyon, a key tributary to Cienega Creek. All of these factors speak to the need for proactive management actions such as purchasing water rights and protecting upland areas of the Cienega Creek watershed.

Introduction

Figure 1. The lush aquatic and riparian resources of the Cienega Creek Natural Preserve provide habitat for endangered species are an important drinking water source for Tucson.

The Cienega Creek Natural Preserve (Preserve) is the most significant aquatic and riparian property in Pima County's extensive preserve network. The Preserve was established in 1986 and is more than 4,000 acres in size (over 6 square miles) and stretches along the last 12 miles of Cienega Creek before the creek drains into the Pantano Wash.

The Preserve contains some of the region's best examples of mesic riparian forest, with its associated tall cottonwood, willow, and mesquite trees that were once abundant along streams and rivers of southern Arizona. Unlike the nearby Santa Cruz River, which is much different now than it was historically, Cienega Creek retains some characteristics of its former hydrological and ecological function. The precious open water and lush marsh and mesic riparian vegetation along Cienega Creek (Figure 1) provide habitat for two species of endangered fishes (the Gila topminnow and Gila chub), one endangered plant (Huachuca water umbel), species of interest such as the Mexican garter snake (Rosen and Caldwell 2004) and lowland leopard frog, and hundreds of other plants and animals that rely on this rare resource. What is perhaps most unique about the Preserve is that all of these resources occur in such close proximity to the Tucson metropolitan area (Figure 2). Because of its perennial flow, good water quality, and role as wildlife habitat, Cienega Creek has been designated one of Arizona's "Outstanding Waters" by the Arizona Department of Environmental Quality (Fonseca 1993).

The Preserve was established for "the purposes of the preservation and protection of the natural and scenic resources of the property…for the benefit and protection of the County, its resources, residents, and visitors". Specifically, the management objectives (from McGann and Associate Inc. 1994; Pima County Regional Flood Control District 2009) for the Preserve are to:

1. Preserve and protect the perennial stream flow in Cienega Creek;
2. Preserve and protect the existing natural riparian community along the stream corridor;
3. Provide opportunities for public use of the Preserve for recreation, education, and other appropriate activities.

Since its establishment, the Preserve has undergone significant changes, due in part to management actions such as the exclusion of cattle soon after its establishment. Since that time, the lush cottonwood and willow gallery forest has returned to the Preserve (Figure 3).

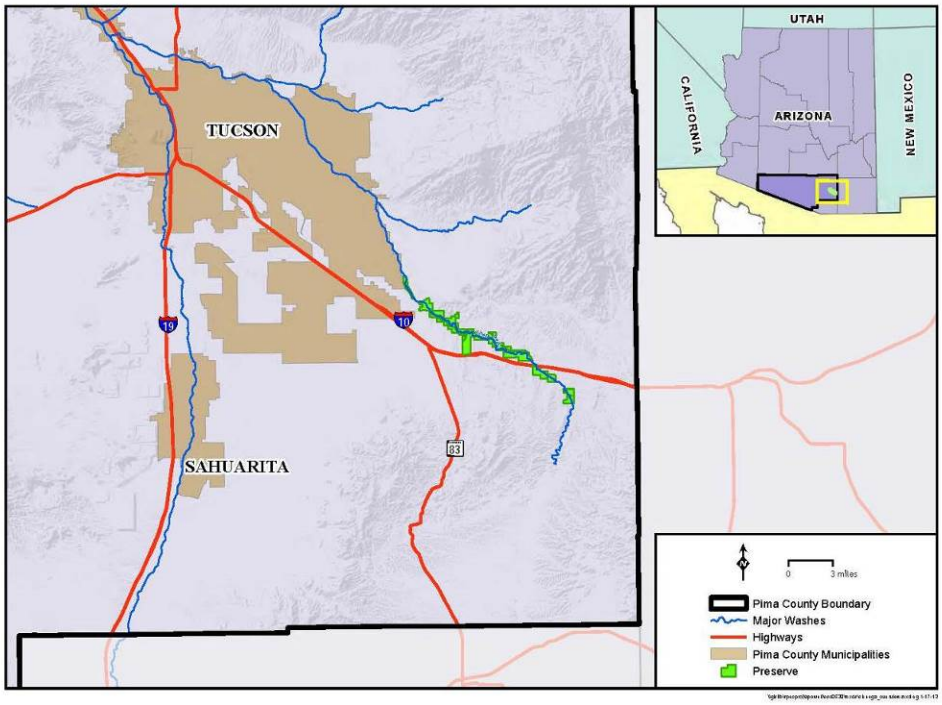


Figure 2. Location of Cienega Creek in relationship to Tucson and the southwestern U.S.

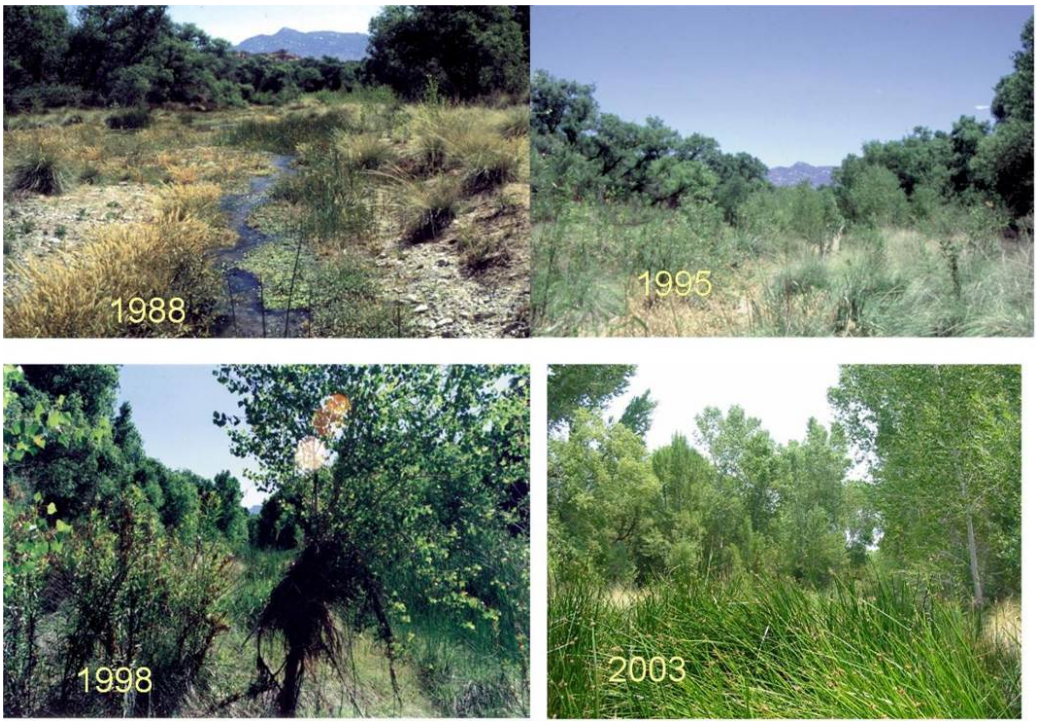


Figure 3. Changes in the vegetation community at the Cienega Creek Natural Preserve following the removal of cattle, which began in 1988 (photographs by the Pima County Regional Flood Control District).

The key resource in the Preserve is water, and without it, the Preserve would be like so many dry and shrub-lined washes of the region. Pima County has focused increasing effort toward the monitoring and enhancement of water and associated aquatic and riparian resources. This focus is all the more important given the Preserve's close proximity to Tucson and the associated development pressures.

These pressures have become a considerable concern for the long-term health and vibrancy of the Preserve considering the reliance of many exurban development projects on pumping groundwater for domestic use. The Pima County Regional Flood Control District (RFCD) began monitoring water and associated resources in 1987 because of planned development within the Cienega Creek watershed and the County pursuit of Outstanding Waters designation for Cienega Creek (Fonseca 1993). Though some of the planned development was never realized, maintaining water monitoring at the Preserve became a top priority for the RFCD and the Pima County Natural Resources, Parks, and Recreation Department (NRPR), which co-manage the Preserve (Pima County Regional Flood Control District 2009). Currently, water monitoring at the Preserve is funded by RFCD and is carried out by the Pima Association of Governments (PAG).

The purpose of the current monitoring effort is to establish baseline hydrologic conditions for comparison purposes, in the event that future groundwater development or land-use changes occur in the vicinity of Cienega Creek (Pima Association of Governments 2011). Though this monitoring effort is ongoing and PAG regularly provides the RFCD and NRPR with annual updates on monitoring activities (e.g., Pima Association of Governments 2011), there has not been a thorough review of the long-term datasets since 1998 (Pima Association of Governments 1998).

This report provides a summary of much of the water data that has been collected at the Cienega Creek Preserve, and—if applicable—elsewhere in the Cienega watershed. I look specifically at: 1) precipitation, 2) streamflow and discharge, 3) surface water extent, and 4) depth to groundwater. I also put precipitation data from the Cienega watershed in a regional context. I do not summarize or investigate trends in water quality data. The period of interest varies by the parameter being investigated because of when monitoring began, but for all parameters the analysis period ends in 2011, the last complete year of data that was available when this project began (October 2012).

For parameters that are included in this report, I investigate trends and correlations among monitoring parameters, potential threats to those resources, and what (if any) management action can be taken to address these trends. Specifically, the goals of this report are to:

- Summarize most of the water-related monitoring data that has been collected at the Preserve and elsewhere in the watershed;
- Where feasible and appropriate, identify statistically and ecologically significant trends in those data;
- Provide potential explanations of observed trends;

Methods

The level of data summary and analysis for this effort depends on the data themselves. For some data, I summarize observations in graphical format, but do not perform statistical analyses because such an approach may not be statistically valid, either because the data were not collected using the same method or at the same location over time or because the data were too sparse for statistical analyses. For most data, the methods of collection and length of collection were sufficient to investigate long-term trends. In these instances, I always checked the distribution of observations before any statistical analyses to ensure that parametric assumptions of normality were met. If not, I transformed the data to meet these assumptions and in all cases, used the natural logarithm.

The type of statistical analysis varies by the parameter of interest. For many of the parameters, I investigated long-term trends by way of a linear function and for many parameters I used the Seasonal Kendall test, which was developed by the USGS in the 1980s and has become the most frequently used test for trends in the environmental sciences (Yue et. al. 2002; Hensel and Frans 2006) including river flow data (Douglas et. al. 2000). The Seasonal Kendall test performs separate tests for trends in each season (months, unless otherwise noted), and then combines the results into one overall linear trend result. The Seasonal Kendall test accounts for seasonality by computing the Mann-Kendall test on each season separately, and then combines the results blocks out all seasonal differences in the pattern of change (Hensel and Frans 2006). No comparisons are made across seasonal boundaries and this is important because water resources in our region often change within a year based on the bimodal precipitation patterns of the area. I note the results of the Kendall test in the text of the document, but also show the results graphically and report the linear (monthly) trends and the associated statistics from linear regression analysis. In each section, below, I provide further details and justifications for the data summary and analysis method(s) used.

Precipitation Data

Data Collection. The primary focus of this report is on water resources, so it is appropriate to begin with an analysis of precipitation. The Pima County RFCD operates and maintains a network of real-time sensors used to collect data on precipitation, stormwater runoff, and other meteorological conditions. The precipitation gages are tipping buckets, which measure rainfall depth in 1mm increments (but reported values are in inches). Using radio telemetry, sensors report data in the National Weather Service Automated Local Evaluation in Real Time (ALERT) format. ALERT system sensors are event driven and transmit data in real-time to base station computers at the District's office and the Tucson National Weather Service office. Currently, the ALERT system includes 93 precipitation, 36 stream, and 4 weather station sites located in Pima and adjacent counties. There are seven precipitation gages in the Cienega watershed (numbers 4410, 4310, 4320, 4290, 4250, 4270, 4280; Figure 4). For this report, precipitation data are summarized for the period January 1990 through December 2011. Data gaps exist for some gages. For example, gages 4410, 4290,

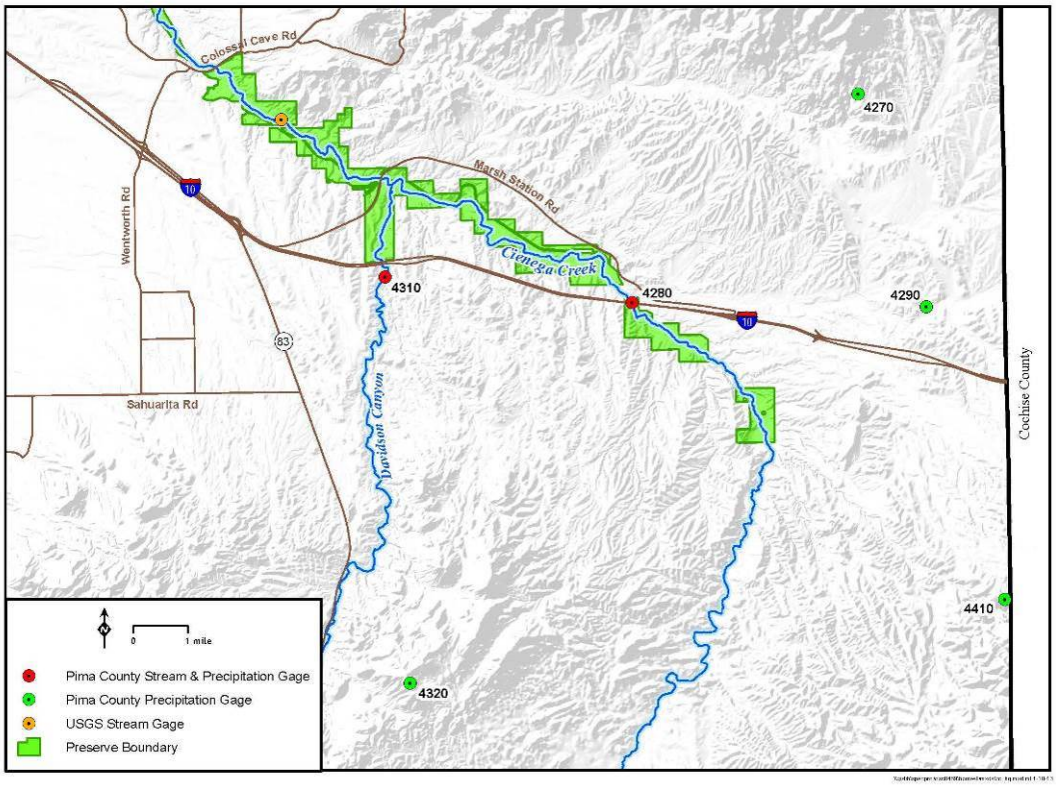


Figure 4. Location of precipitation and/or stream gages in relation to the Cienega Creek Natural Preserve. The USGS Stream Gage is the "Pantano Wash Near Vail, AZ" (site #09484600).

and 4270 were not in operation until 1993, while some gages were inoperable for a few time periods from 1990-2011. In general, the precipitation record for the Cienega Creek watershed is fairly robust and informative.

Analysis. Raw data are collected continuously at these gages, but for this analysis I obtained a monthly precipitation total for each gage. Using these data I first summarized mean annual precipitation $\pm$ 1 SD across all seven sites to understand the spatial distribution of precipitation in the watershed. I tested for linear trends in annual rainfall from 1990 through 2011 using linear and polynomial regression. Polynomial regression is a form of linear regression in which the relationship between the independent variable *x* and the dependent variable *y* is modeled as an *n*th order polynomial. I tested for 2nd and 3rd order polynomials and looked for the combination of variables that explained the most variation in the data, as expressed by R^2. Polynomials are useful for data such as precipitation, which can be cyclical among years. I also investigated seasonal precipitation patterns using one-way analysis of variance (ANOVA), where seasons were noted as: Winter (October-April) and Summer (May-September), which correspond to annual precipitation regime of our region (i.e., winter precipitation patterns come primarily from the Pacific Ocean and summer monsoon

moisture comes primarily from the Gulf of Mexico). I also looked for spatial trends in precipitation; that is to determine if there were differences in precipitation over time among the different gages. I used multiple regression for this using gage, year, and gage*year interaction. I also tested for differences in monthly precipitation data among gages using the Tukey-Kramer, which is used in conjunction with an analysis of variance to look at differences among groups (in this case, gages).

Finally, precipitation data was used as a key explanatory variable throughout this document; in other words to explain observed changes in other parameters. Where precipitation was used for this purpose, it is explained in the appropriate section, below.

Streamflow

Streamflow in Cienega Creek was measured using two primary methods: 1) a hand-held flow meter, 2) continuous discharge measurements from the permanent USGS stream gage at Pantano and 3) during discrete flooding events at two stream gages located near I-10 (at Davidson Canyon and Cienega Creek; see Figure 4).

Flow Measurements Using Hand-held Meter

Streamflow volume is the quantity of surface water and is typically measured in cubic feet/second (CFS). Direct measures of streamflow have been taken at various times and using various methods since 1979. Data were collected sporadically and with unknown equipment during the late 1970s and early 1980s. Because no information is available on these methods of data collection, they are not included in this report. Instead, I summarize the two efforts that are well documented and that collected data at the same two sites over time at: 1) Marsh Station Road Bridge, downstream from the Cienega/Davidson confluence, and 2) Tilted Beds, several miles upstream from Marsh Station; Figure 5).

<u>Arizona Outstanding Waters effort, Arizona 1987-1993</u>. The RFCD, PAG, and the Arizona Department of Environmental Quality (ADEQ) collected baseline data for the designation of Cienega Creek as an Arizona Outstanding Waters. It is not known what specific instruments were used, but Fonseca (1994) indicates that a current meter was used. Measurements were made on a single occasion for an instantaneous measurement of flow, which is assumed to represent the baseflow for that sampling period. The number and timing of sampling was inconsistent, especially at the Tilted Beds site (Table 1).

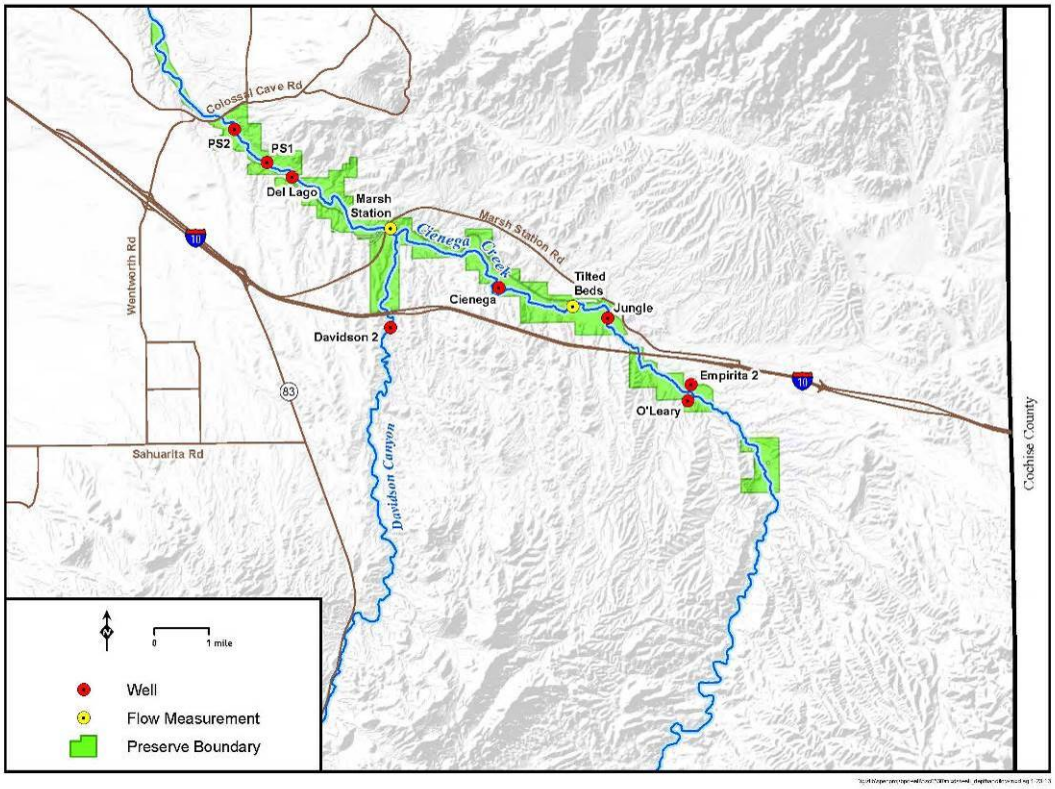


Figure 5. Location of flow measurement and well monitoring sites in the Cienega Creek Natural Preserve.

Table 1. Number of stream flow sampling events in support of the Arizona Outstanding Waters designation at two sites along Cienega Creek at the Cienega Creek Natural Preserve.

	Site	
Year	Tilted Beds	Marsh Station
1987		3
1988		5
1989	5	6
1990	2	6
1991	0	6
1992	1	6
1993	1	2

Pima Association of Governments, 1993-2011. PAG continued the previous effort starting in 1993, though sampling events were inconsistent until 1996. Since that time, PAG has consistently monitored flow at the two monitoring sites in each month of the year. PAG used a pygmy flow meter (Qualimetrics brand, Model 6660) and calculated discharge in CFS. To accurately represent baseflow, monitoring did not take place if a significant rainfall event occurred within three days prior to a scheduled field event. If a precipitation event did occur within three days, sampling was postponed until drier conditions prevailed. (However, a review of the data for both sites revealed that on a few occasions flood events were

occurring. Data were recorded noted as "flood event", but these data were excluded for this analysis.) Streamflow measurements were taken at a location along the stream where the channel was relatively straight and streamflow was fairly uniform. When possible, points of converging and diverging flow paths were avoided. Because stream form can change between monthly visits, the actually monitoring locations varied by up to 10 m. The pygmy meter was sometimes employed at the Tilted Beds site, but the stream velocities at that site were often too low to be accurately measured using this method. Therefore, most discharge measurements at the Tilted Beds site were made by catching the flow into 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.

Data Analysis. For the Marsh Station Bridge site, I performed a seasonal Kendall test from 1990-2011. I also used logistical regression for each of the 12-months of sampling, with the total number of years in each monthly test dependent on the start of sampling in that particular month. That is, because some years and months did not have data, logistical regression was performed starting at the first month and year of data collection. Because of the high number of visits with no flow at the Titled Beds site, I did not perform statistical analyses on these data, but I present them in box plots to show the distribution of information. Box plots are a convenient way of graphically depicting groups of numerical data using 5-number summaries: the smallest observation (sample minimum), lower quartile (Q1), median (Q2), upper quartile (Q3), and sample maximum.

Baseflow Volume: Stream Gaging Stations

Summary of the Data. Permanent stream gaging stations are one of the most important tools in the U.S. for measuring and monitoring streamflow. Streamflow is measured via a float device within the steel housing of the gage (Figure 6). This float marks the stage height, which is converted to cubic feet/second by way of calculating the stream channel characteristics. Technicians periodically visit the site to check for problems and recalibrate the flow measurements. Data are collected approximately every 15 minutes, though it can be more frequently during high-flow events. There are three stream gages within the Preserve. The primary gage is administered by the USGS (gage #9484600) and is located along the Pantano Wash near Vail (Figure 4). Two other gages are run by the Pima County Regional Flood Control District and the gages are located near to I-10 in both Cienega Creek (gage #4283; see Figure 4) and Davidson Canyon (gage #4313). Those gages differ somewhat from the USGS gage in that the RFCD gages consist of a pressure transducer within a conduit housing to measure stream height in real time and on an event-driven basis. For analysis, I

Figure 6. The permanent USGS stream gage at the Pantano Wash site, 2010.

used data from all three rain gages from January 1, 1990 through-December 31, 2011 and obtained mean daily discharge (cubic feet/second) measurements for each of the >8,000 days during this time period.

The two gages located along Davidson Canyon and Cienega Creek are located along currently ephemeral reaches of the two creeks. Because the gages record streamflow only during a flood, there were few measurements from these gages. From 1990-2011, the Davidson Canyon gages recorded data on 95 days and the Cienega Creek gage on 160 days during the same period.

The Pantano gage, an official USGS streamgage, is located in a perennial-flow section of the Pantano Wash before the water is diverted to Del Lago golf course (Figure 6). This gage recorded a continuous baseflow measurement record from 1990-2011. Observations are reported as mean daily CFS.

Analysis. I summarized the number of days in each year where data were recorded at each of these gages and calculated total annual discharge in acre-feet. I did not test for trends in the actual discharge measurements (i.e., mean daily discharge) because of the high number of days with no measured streamflow (i.e., many 0 values). By contrast, the Pantano Wash gage had a continuous streamflow and therefore the opportunity to discover trends was greatest. For the analysis of the Pantano gage, I first summarized the mean + SD for each month over the 21-year record to test for the seasonality of streamflow among months.

The overall Seasonal Kendall trend slope for data from the Pantano Wash gage was computed as the median of all slopes between data points within the same season (month). To prepare the data for the Seasonal Kendall test, I obtained the median monthly flow rate, because the median rate better reflects baseflow conditions (as opposed the mean, which can be influenced by extreme flooding events). I also plotted median annual discharge from 1990-2011 to graphically show the trends in baseflow conditions over time.

Comparison of Flow Measurements and the Pantano Stream Gage

Analysis. I sought to understand two sets of relationships between data sets to better understand the dynamics of the system and to inform the efficiency of monitoring in the future. The two comparisons of Streamflow were: 1) Tilted Beds to Marsh Station Road and 2) Marsh Station Bridge to the Pantano gage. I used a pairwise correlation comparison. This is matrix of correlation coefficients that summarizes the strength of the linear relationships between each pair of response (Y) variables, in this case monthly streamflow measurements. For these analyses, I included only those observations from January 1995 to December 2011, which represented the most continuous period of record. I excluded those pairs of observations for which there was no flow at the Tilted Beds site. In the comparison of Marsh Station Bridge to the Pantano gage, I used the median measurement at the Pantano gage to represent the baseflow conditions of the stream. I also used the median flow for the first 10 days of each month, because no data existed on which day discharge data were collected by PAG, though the data collection period for PAG was approximately in the first week of each

month. After performing an overall correlation analysis, I sought to understand seasonal differences in these observations. Therefore, I performed separate analyses for each month of the year, irrespective of trend over time.

Comparison of Flow to Precipitation

I used the monthly rainfall totals, averaged among all seven precipitation gage sites within the watershed, to determine the influence of precipitation on streamflow discharge, as measured at the Pantano gage. For the Pantano gage I used the mean daily flow measurement from the last day of each month from 1990-2011. I used the last day because precipitation totals for each month go through to the last day of each month. For this analysis I used multiple regression and in addition to precipitation measurements, I also included other variables to explain variations in the data. Specifically, I tested for the effect of year, month, and year*month interactive effect.

Extent of Streamflow (Wet/Dry Mapping)

Methods. Wet/dry mapping has a relatively long history at Cienega Creek, with the first data collected in 1908 (Fonseca 1993). The next mapping efforts in the mid and late-1970's and early 1980's were sporadic, but from late 1984-1991, there was a consistent record of sampling 4-5 times per year (Table 2). Data during this period were collected by way of aerial photography over the creek, which was paid for by a company seeking approval of a proposed development near the Preserve (Julia Fonseca, *personal communication*). Julia Fonseca interpreted these aerial images as part of the County's instream flow application for Cienega Creek (Fonseca 1993). The survey area for this effort was from just downstream of where Cienega Creek crosses under Interstate 10 (east side) to the Pantano Dam (west side). As part of the current reporting effort, Mike List (Pima County IT department) translated the Data from Fonseca 1993 and input these data into a GIS layer for this analysis. These data will be posted to the County's GIS library for future reference. On three occasions (one occasion in 1974 and two occasions in 1988) there was an incomplete survey of the creek; those data were excluded from this analysis.

From 2001-present, the PAG has carried out quarterly monitoring (March, June, September, and December) at much the same location as previous efforts, except they exclude a 1.5 mile stretch starting downstream of the confluence of I-10 and Cienega Creek. That stretch is included in this analysis as "dry" because repeated surveys along that stretch have found this to be the case; the last time it was known to have baseflow was in the 1980's. The PAG effort involves mapping by way of walking the length of the creek channel and marking the location (or start/stop points) of surface water in the creek. PAG has also conducted walk-throughs on Lower Davidson Canyon near its confluence with Cienega Creek since 2001 and in upper Davidson Canyon, south of Interstate 10 on the County's Bar V property, since 2005. Those data are not summarized in this report. Also not summarized are data from March, September, and December 2010 and 2011; those data were collected, but have not been analyzed by PAG.

Table 2. Summary of perennial surface mapping at the Cienega Creek Preserve since 1974. Because sampling occurred at different months and dates over time, seasons are defined as: Winter: 11/15-1/31, Spring: 2/1-3/31, Pre-monsoon: 4/1-7/1, Monsoon: 7/2-10/1.

	Season			
Year(s)	Spring	Pre-monsoon	Monsoon	Winter
1975			X	
1976-77		No surveys		
1978			X	
1979				X
1980-81		No surveys		
1982				X
1983		No surveys		
1984			X	X
1985		X	X	X
1986	X	X	X	X
1987	X	X	X	X
1988	X	X	X	X
1989	X	X	X	X
1990	X	X	X	X
1991	X	X	X	X
1992-98		No surveys		
1999		X		
2000		X		
2001		X	X	X
2002	X	X	X	X
2003	X	X	X	X
2004	X	X	X	X
2005	X	X	X	X
2006	X	X	X	X
2007	X	X	X	X
2008	X	X	X	X
2009	X	X	X	X
2010	X	X	X[a]	X[a]
2011	X[a]	X	X[a]	X[a]

X[a] Data collected but not analyzed.

Analysis. The total length of streamflow for each sampling event was determined through GIS analysis of the data and summarized as number of miles with perennial flow. I performed linear regression analysis using all observations and seasons, but also separated analyses for each season. I used the monthly rainfall totals, averaged among all seven sites within the watershed, to determine the influence of precipitation on surface water extent. For this analysis I used multiple regression included other variables to explain variations in the surfacewater data. Specifically, I tested for the effect of year, month, and year*month interactive effect, and precipitation from the previous month because of the time lag between precipitation and flow extent conditions.

Depth to Groundwater

Methods. Depths to groundwater were measured at eight wells with either a Solinst Water Level Meter or with in situ transducers. The monitoring wells are distributed throughout the Preserve but occur in different geological contexts. On a monthly basis and when accessible,

PAG monitored the O'Leary, Jungle, Cienega, Del Lago 1 and Empirita 2 well sites. The Davidson 2 was monitored on a quarterly schedule. The PS-1 and PN-2 wells were monitored four times a day by ADWR transducers and the data was summarized as the mean measurement per month.

Analysis. I tested for linear trends for each of the 8 wells using linear regression. I used the monthly rainfall totals, averaged among all seven sites within the watershed, to determine the influence of precipitation on depth to water in the wells that were mentioned previously. For these analyses I used multiple regression. Precipitation was for the one and two months prior to measurement of depth to groundwater. I also included other variables to explain variations in the data, specifically, I tested for the effect of year, month, and year*month interactive effect.

Drought: A Look at Regional Climate

Methods and Analysis. Changes in water characteristics at Cienega Creek such as streamflow and volume are the result of a host of site-specific factors such as rainfall and land-use within the watershed. Broader-scale climate factors are also key to understanding changes at Cienega Creek and a key dataset is the Palmer Drought Severity Index. The index was developed by Wayne Palmer in the 1960s and uses temperature and rainfall information in a formula to determine dryness. It has become the semi-official drought index and is most effective in determining long term drought—a matter of several months—and is not as good with short-term forecasts (a matter of weeks). It uses a 0 as normal, and drought is shown in terms of minus numbers; for example, minus 2 is moderate drought, minus 3 is severe drought, and minus 4 is extreme drought. I summarized data from "southeastern" Arizona, which includes Pima, Santa Cruz, and Cochise counties. Data are summarized monthly from 1895-2011 and from 1990-2011, the focal period for this report. These data were used to understand if the observed patterns at the Preserve could be explained, in part using the broader, regional trend in the Palmer index.

Results

Precipitation

From 1990-2011, mean annual precipitation was 11.2 inches and ranged from 6.5 inches in 2009 to 15.1 inches in 2000 (Figure 7), which was similar to areas around the Tucson basin. As was expected, precipitation varied by month, when averaged across all seven sites within the Cienega watershed (Figure 8), with July and August having the greatest total rainfall of any other month and together accounting for one half of the average annual rainfall.

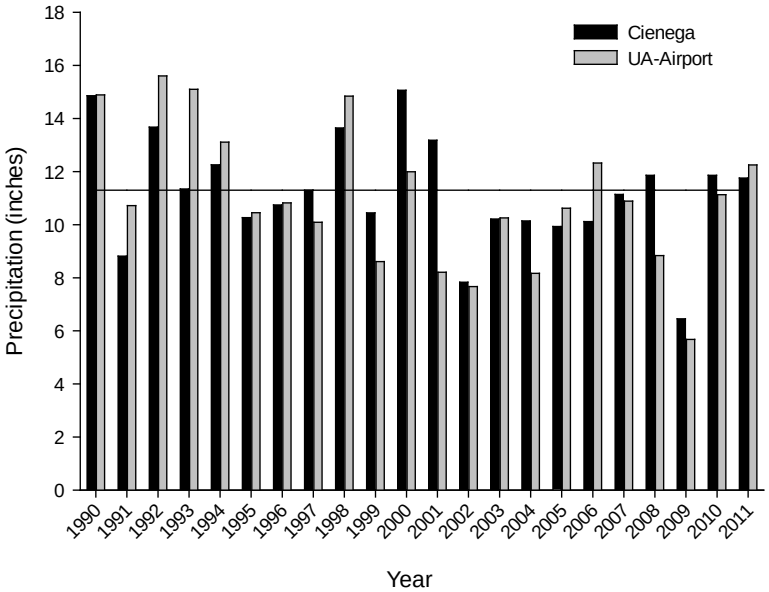


Figure 7. Total annual precipitation averaged among all seven sites in the Cienega Valley and compared to the mean annual precipitation, averaged for both the University of Arizona (UA) and the Tucson International Airport. Solid line is the long-term average at the Tucson International Airport.

There was considerable inter-site variation in rainfall during the period of record, with sites varying in total annual rainfall (one-way ANOVA; $F_{6,126} = 9.28$, $P = <0.001$), after accounting for the effect of year. Mean annual rainfall was highest for the Davidson Canyon gage (site 4310; 13.9 $\pm$ 3.8 [SD] inches) and lowest for the Empire Peak gage (site 4310; 7.5 $\pm$ 2.6 [SD] inches). The other four sites were not statistically different (based on Tukey-Kramer HSD test at 95% difference) and all had mean annual precipitation measurements of approximately 10.5 inches. Taken together, the combination of site and year was a good predictor of mean annual rainfall (multiple linear regression; $F_{27, 117} = 9.3$, $P = <0.001$, $R^2 = 0.64$).

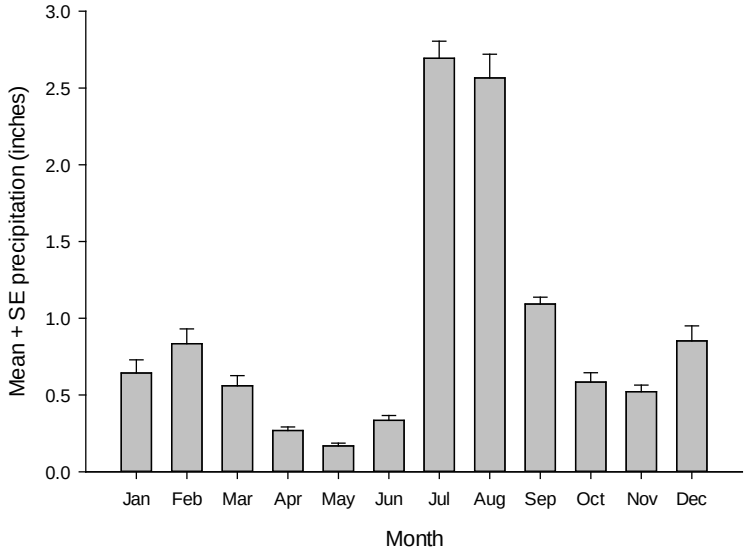


Figure 8. Mean monthly precipitation ($\pm$ 1SE), averaged across the seven gage sites in the Cienega watershed, 1990-2011.

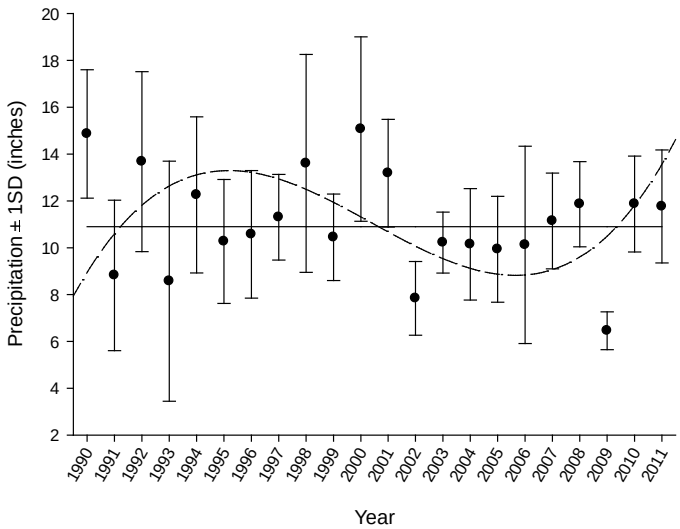


Figure 9. Mean precipitation from seven precipitation gages near the Cienega Creek Natural Preserve. Solid line is the mean annual precipitation for this period of record. Dashed line is the 3rd order polynomial that maximizes the amount of variation explained in the data. Error bars are larger for 1993 in part because data existed for only 5 sites.

From 1990-2011, there was a negative trend in precipitation, but after taking into account the effect of the precipitation gage, there was no statistically significant linear trend (multiple regression $F_{1,131}$ = 0.57, P = 0.45, R^2 = -0.003). I also fit a set of polynomial models to help explain variation in the data (Figure 9). The model that explained the most variation in the data was a 3rd order polynomial (Figure 9; $F_{3,56}$ = 3.5, P = 0.02, R^2 = 0.06), which shows the cyclical nature of wet and dry periods in the Cienega watershed during this period. There was no spatial trend in precipitation among sites (multiple regression $F_{6,6}$ = 0.53, P = 0.77).

Mean monthly summer rainfall (June-October) averaged 6.8 inches, while winter rainfall (November-May) averaged 4.1 inches (*t*-test for difference among group; t_{263} = 11.2, P = <0.0001). Despite seasonal changes in mean monthly precipitation totals from 1993-2011, there was no statistically significant trends within the summer (linear regression on log-transformed data; $F_{1,82}$ = 1.5, P = 0.21, R^2 = 0.006; Figure 10) nor the winter months ($F_{1,82}$ = 1.7, P = 0.17, R^2 = 0.007; Figure 10).

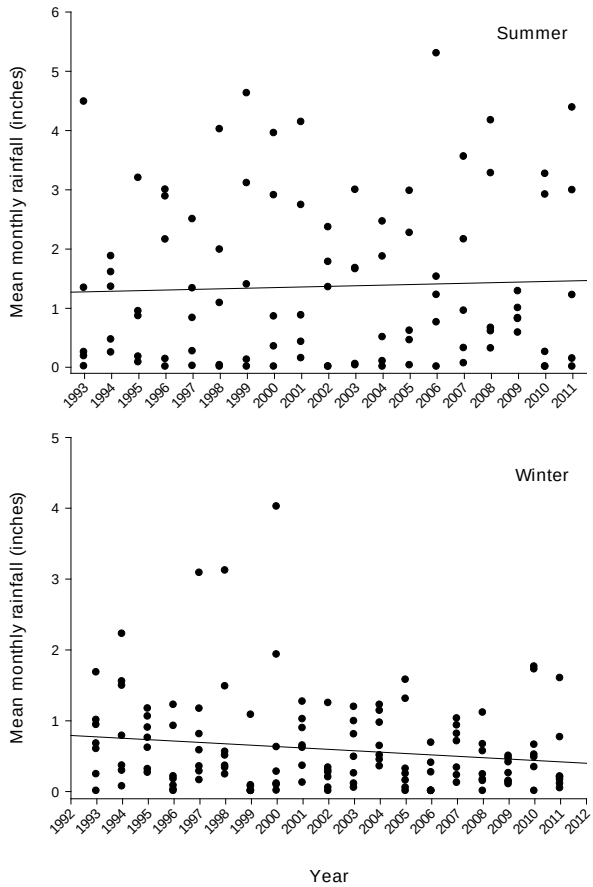


Figure 10. Seasonal differences in precipitation within the Cienega watershed, 1993-2011. Seasons: Winter (October-April) and Summer (May-September). Trends are not statistically significant.

Streamflow: Baseflow and Discharge

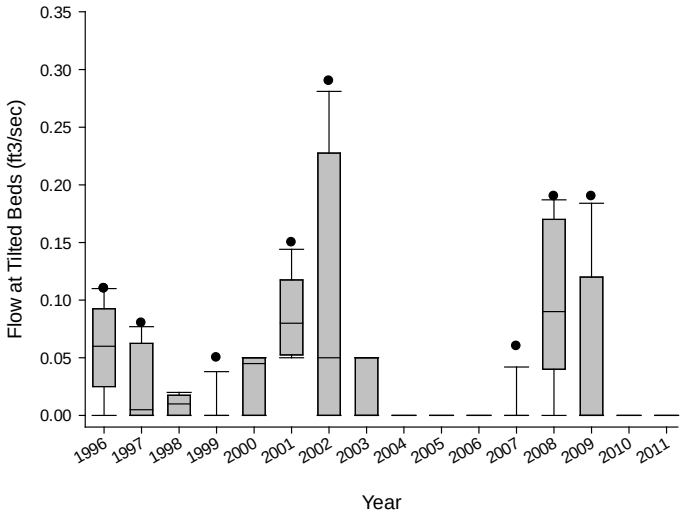
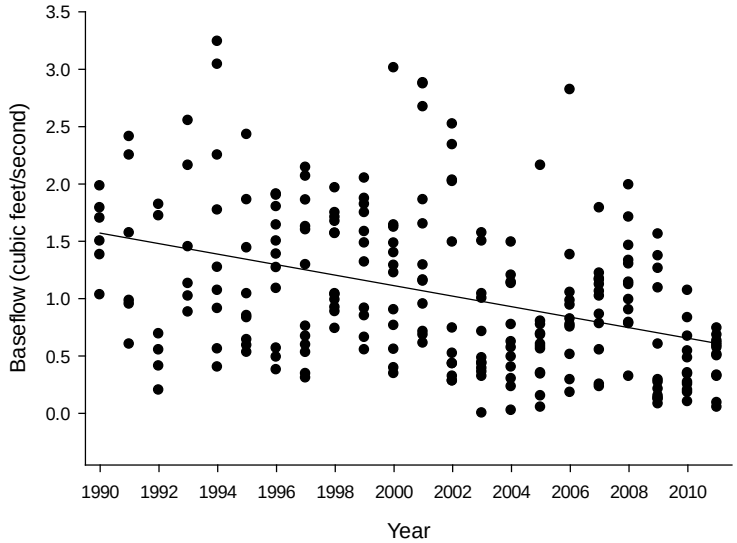


Figure 11. Box plot showing baseflow at the Tilted Beds site. The site was visited in each month during this period of observation, so missing data is the result of no flow observations. Statistical analyses were not performed on these data due to lack of flow at this site over time. Box plots show the variability of flow measurements at these sites.

<u>Baseflow measured using hand-held meters</u>. Baseflow at the Tilted Beds site was sporadic (Figure 11); from 1996-2011, there was no flow in five of the years and in many years, flow was restricted to only a few occurrences.

Baseflow at Marsh Station Bridge showed a significant decline from 1990-2011. This declining trend is confirmed by the Seasonal Kendall Trend Test (slope = 1.485 + -0.05*Time[year]; tau correlation =-0.417, z = -8.68, *P* = 0.0003). A similar trend was found using linear regression ($F_{1,242}$ = 53.4, *P* = <0.0001, R^2 = 0.18; Figure 12). On one sampling occasion (in 2003) there was no recorded flow at the Marsh Station Bridge site.



linear regression analysis. In addition to a decline, the intra-annual dispersion of measurements over time also declined, especially in the last few years of record.

In all but one month there was a negative trend across the period of record (Figure 13). Negative trends in baseflow were statistically significant (i.e., P<0.05) for nine of the 12 months, which also demonstrates important seasonal differences; the months with no statistically significant trend represent the monsoon season (July, August, and September).

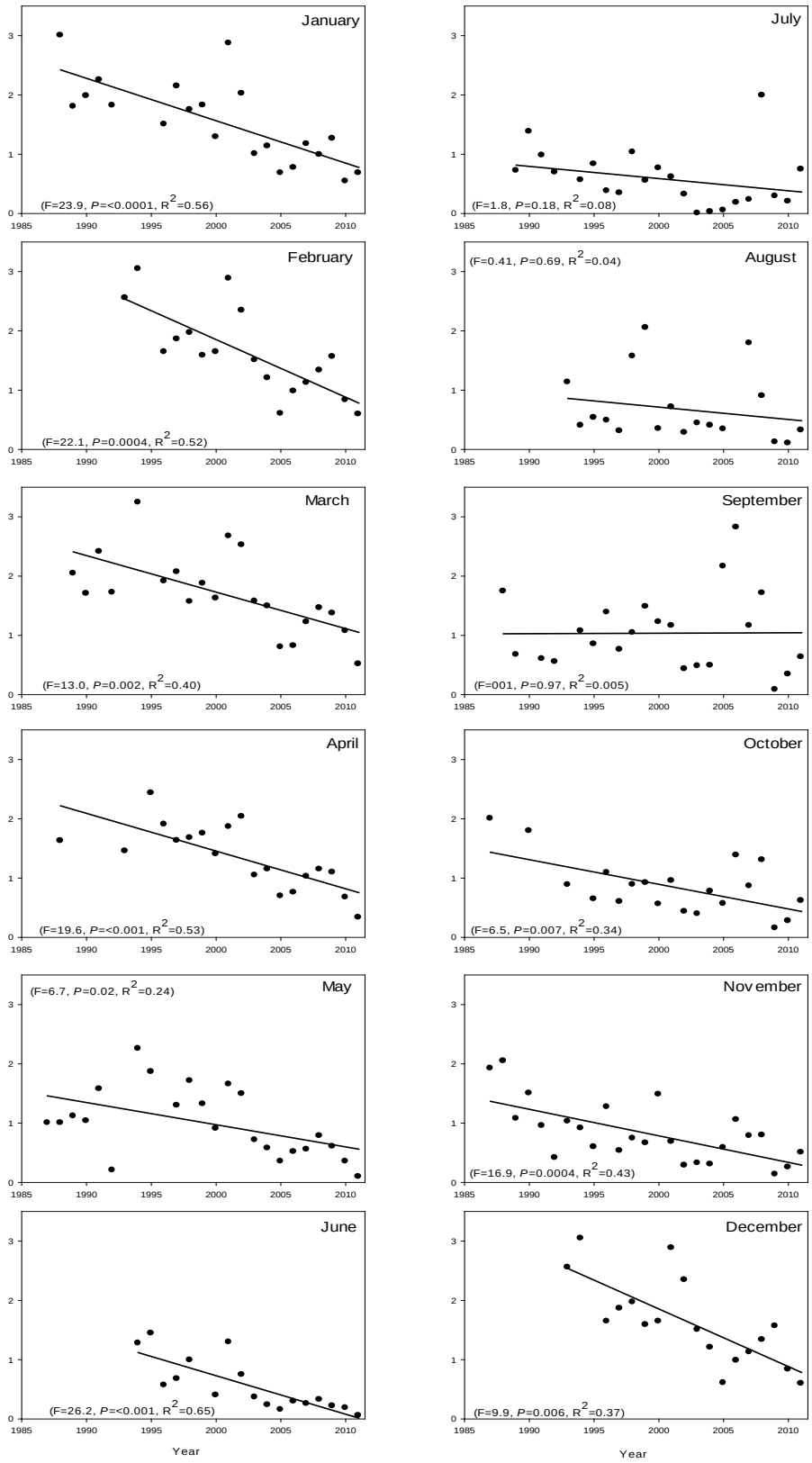


Figure 13. Baseflow measured at the Marsh Station Bridge by month. Statistics and trend lines are from linear regression analysis. Note that the period of record is different for some months.

Discharge measured at gaging stations. The number of days in a calendar year with discharge measurements at the Davidson Canyon gage ranged from zero days (for four years) to a high of 11 days in 2008 (Figure 14). The number of days with measurable flow was highest in 1990 and 2000, with each year having a total of 10 days of recorded flow. These data showed an increasing trend over time, but these trends were not statistically significant (logistic regression, $F_{1,20} = 0.88$, $P = 0.35$, adjusted $R^2 = -0.005$). The Davidson Canyon gage had its highest discharge in 2003, a year when the Davidson gage recorded more water than the Pantano and Cienega gages combined (Figure 15). (Over 60% of the total discharge for the Davidson gage for 2003 was from three days in August 2003 and one day in particular had a total discharge of 603 acre feet, or 31% of the total discharge). Though total annual discharge increased at the Davidson Canyon gage from 1990-2011, the results were not statistically significant (logistic regression, $F_{1,16} = 2.4$, $P = 0.14$, adjusted $R^2 = 0.13$).

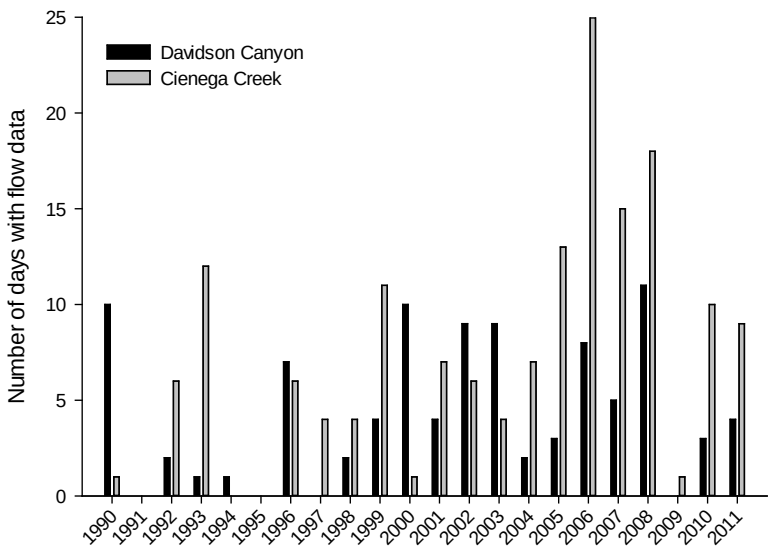


Figure 14. Number of days of measured flow at the Davidson and Cienega Creek gaging stations.

The Cienega Creek site had four years with no measureable discharge, but had seven years with ≥10 days of recorded discharge, including one year (2006) with 25 days of discharge measurements (Figure 14). Discharge at the Cienega Creek gage was highest in 2007 and had a number of years with none or very little measureable discharge, but there was an increasing and statistically significant trend from 1990-2011 (Figure 15; logistic regression, $F_{1,17} = 9.3$, $P = 0.007$, adjusted $R^2 = 0.31$).

For the Pantano Gage, discharge was highest in 1998 with approximately 11,100 acre feet and lowest in 2009 with less than 500 acre feet (Figure 15). There was a significant decline in median monthly discharge from 1990-2011 at the Pantano Wash gage (Figure 16). This declining trend is confirmed by the Seasonal Kendall Trend Test (slope = 0.66 + -0.83*Time[year]; tau correlation =-0.4, z = -5.32, P <0.0001). I also adjusted the model for the effects of precipitation on streamflow, though that did little to improve the model (Seasonal Kendall Trend test with LOWESS smooth; tau correlation =-0.43, z = -5.6, P <0.0001). For graphical purposes, I also plotted the median annual discharge at the Pantano Wash gage (Figure 17).

There was considerable variation in the mean daily discharge by month (Figure 18), with the months representing the monsoon (July, August, and September) having the most variation. This variation may explain why these months were the only months that did not have a statistically significant decline from 1990-2011, which was the case for the other months of the year (Figure 19).

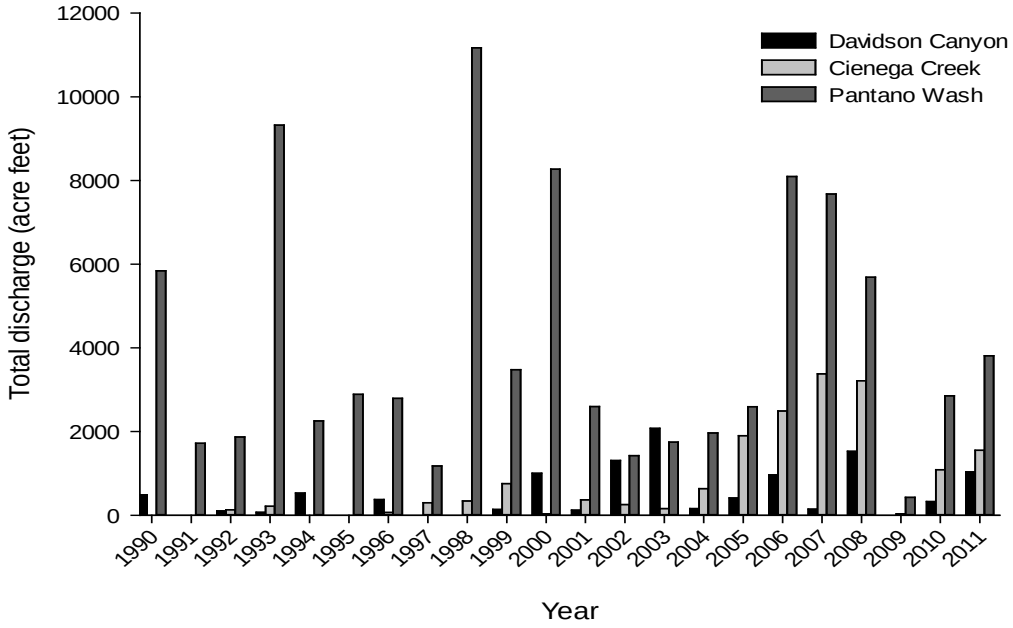


Figure 15. Total annual discharge at the three gages within the Cienega Creek Natural Preserve. Discharge at the Cienega and Davidson gage represented stormflow, whereas at the Pantano gage, total discharge represented both stormflow and baseflow. Stormflow discharge has increased at the Cienega Creek gage despite the drought.

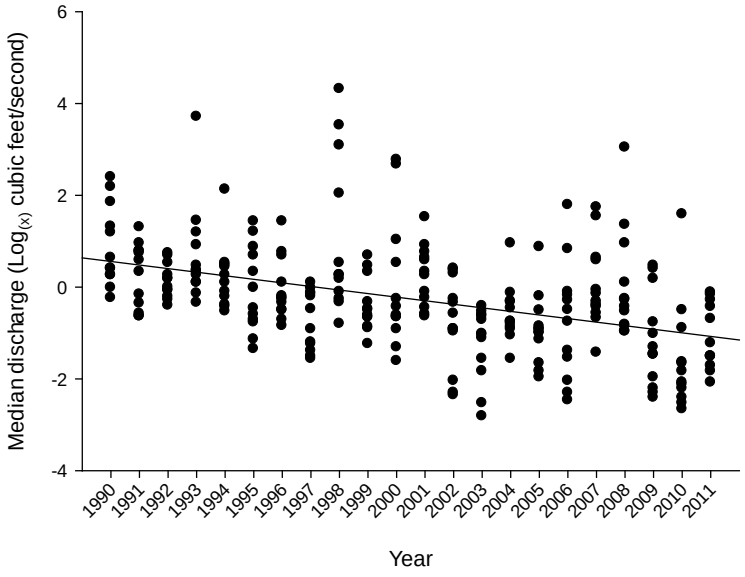


Figure 16. Median monthly discharge (natural log of cubic feet/second) measured at the Pantano Wash gage. Data and linear trend line are for graphical purposes; trend is tested for using the Seasonal Kendall test for trend and reported in the text.

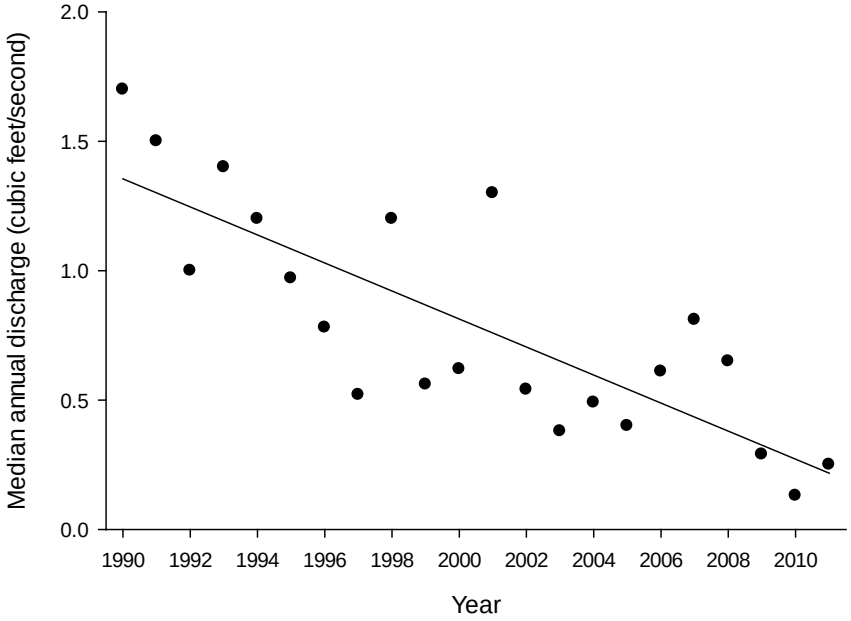


Figure 17. Median annual discharge at the Pantano Wash gage. This is a summary of the data in Figure 16, but data are not log-transformed.

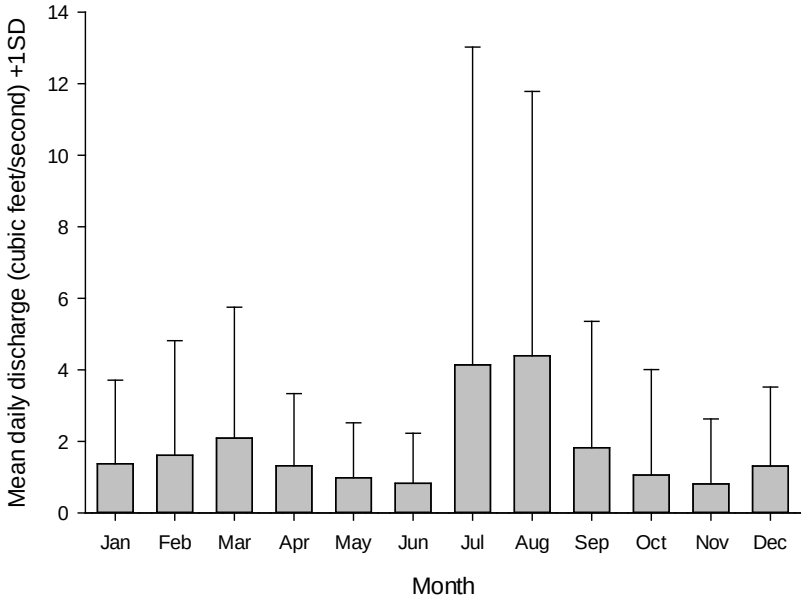


Figure 18. Mean daily discharge by month, in cubic feet/second +1 standard deviation (SD) at the Pantano Wash gage. Notice the variability of measurements in July and August, which are during the monsoon season.

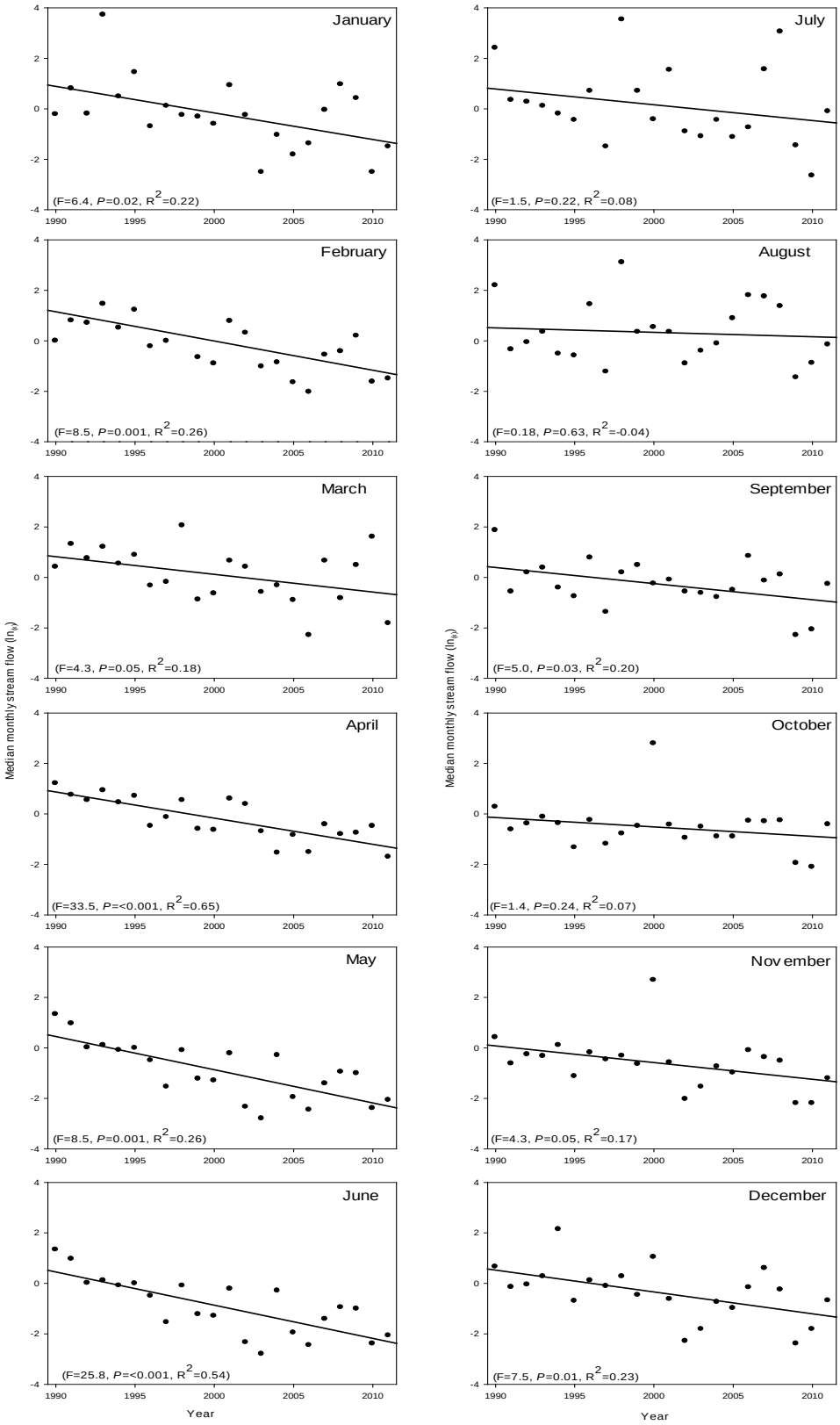


Figure 19. Discharge (natural log) measured at the Pantano gage for each month. Lines and statistics are from linear regression analysis.

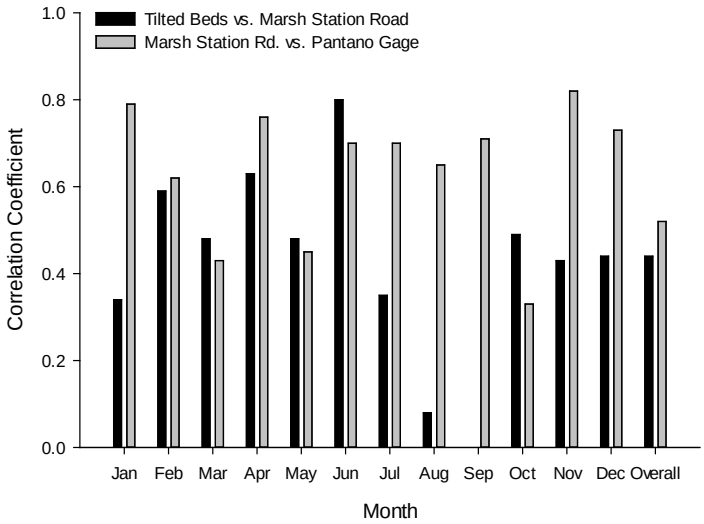


Figure 20. Pairwise correlation between flow measurements taken at the at Tilted Beds and Marsh Station Road and flow measurements at Marsh Station Rd and the natural log of median monthly flow

Influence of Precipitation on Streamflow: Pantano Gage

Mean streamflow discharge at the Pantano gage were most heavily influence by precipitation and year ($F_{4,259}$ = 33.9, P = <0.0001, R^2 = 0.34; Table 3).

Comparison of Streamflow Measurement Data

I compared results of Streamflow monitoring at the Tilted Beds and Marsh Station Bridge sites and found only slight correlation between the two sampling locations (total correlation coefficient = 0.45). However, there were significant differences among months, from a maximum correlation of 0.81 in June to no correlation in September (Figure 20). Comparison of the Marsh Station Bridge and the Pantano gage found a closer overall correlation (correlation coefficient = 0.52) and less monthly variation in the coefficients over time (Figure 20).

Extent of Streamflow

The extent of streamflow declined from a high of 9.5 miles from 1984 through late 1986 to a low of 1.25 miles in June of 2011 (Figure 21). The decline in extent was significant for all four seasons, but greatest in the pre-monsoon (June) and less in the winter (December; Figures 22, 23, 24; Appendix A-D). The variability of flow has also changed during the period of record (1974-2011), from relatively stable flows in the 1980s and early 1990s to highly variable flows from 2001-2009 (Figure 25).

Table 3. Results of multiple regression analysis on the relationship between streamflow discharge (natural log) and other variables thought to influence flow.

Effect	Estimate	F	df	P
Precipitation	0.66	101.9	1	<0.001
Year	-0.06	25.9	1	<0.001
Month	-0.06	6.3	1	0.012
Year*month	0.004	1.3	1	0.25

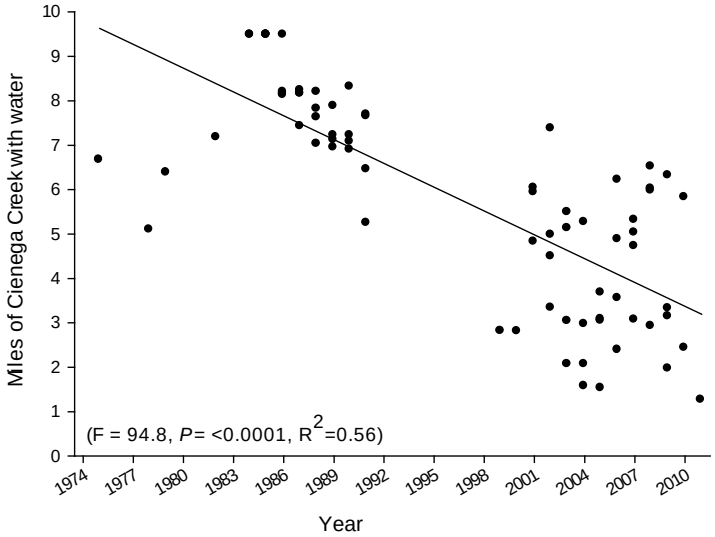


Figure 21. Extent of streamflow at the Cienega Creek Natural Preserve, using all observations. See Figure 22 for summary by season. Maximum flow extent is 9.5 miles. Solid line is from linear regression analysis.

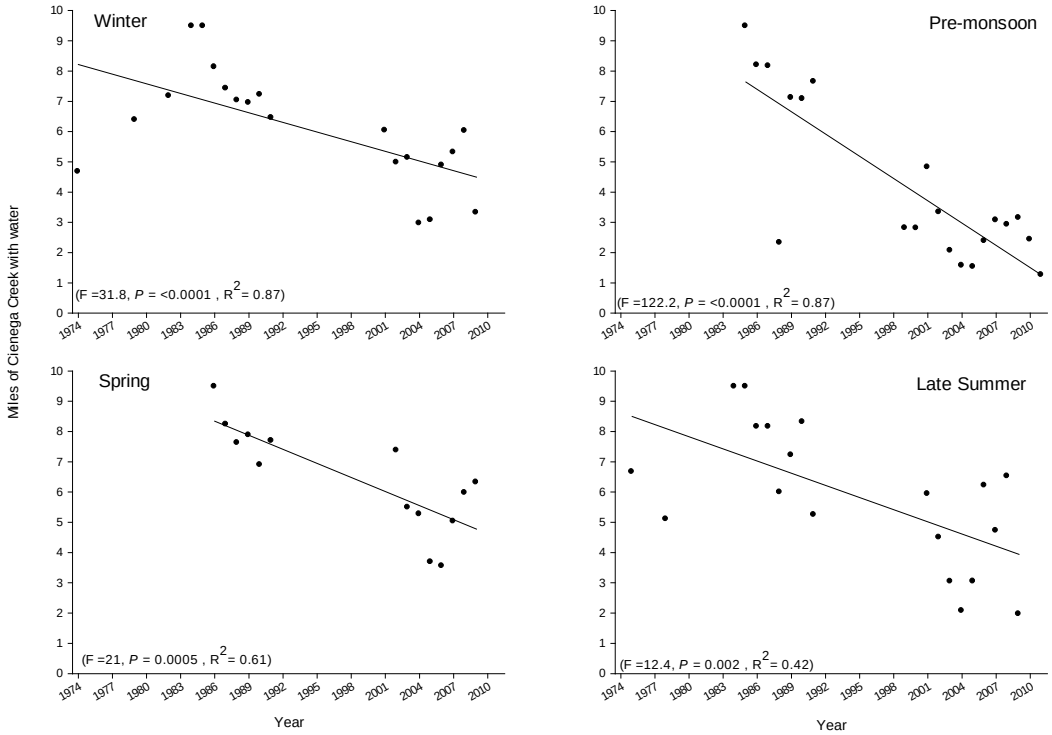


Figure 22. Extent of stream flow at the Cienega Creek Natural Preserve, by season. Maximum flow extent is 9.5 miles. Seasons are defined as: Winter (Nov 15-Jan31); Spring: (Feb 1- March 31); Pre-monsoon: Apr 1-June 30); Late summer (July 1- Nov 1).

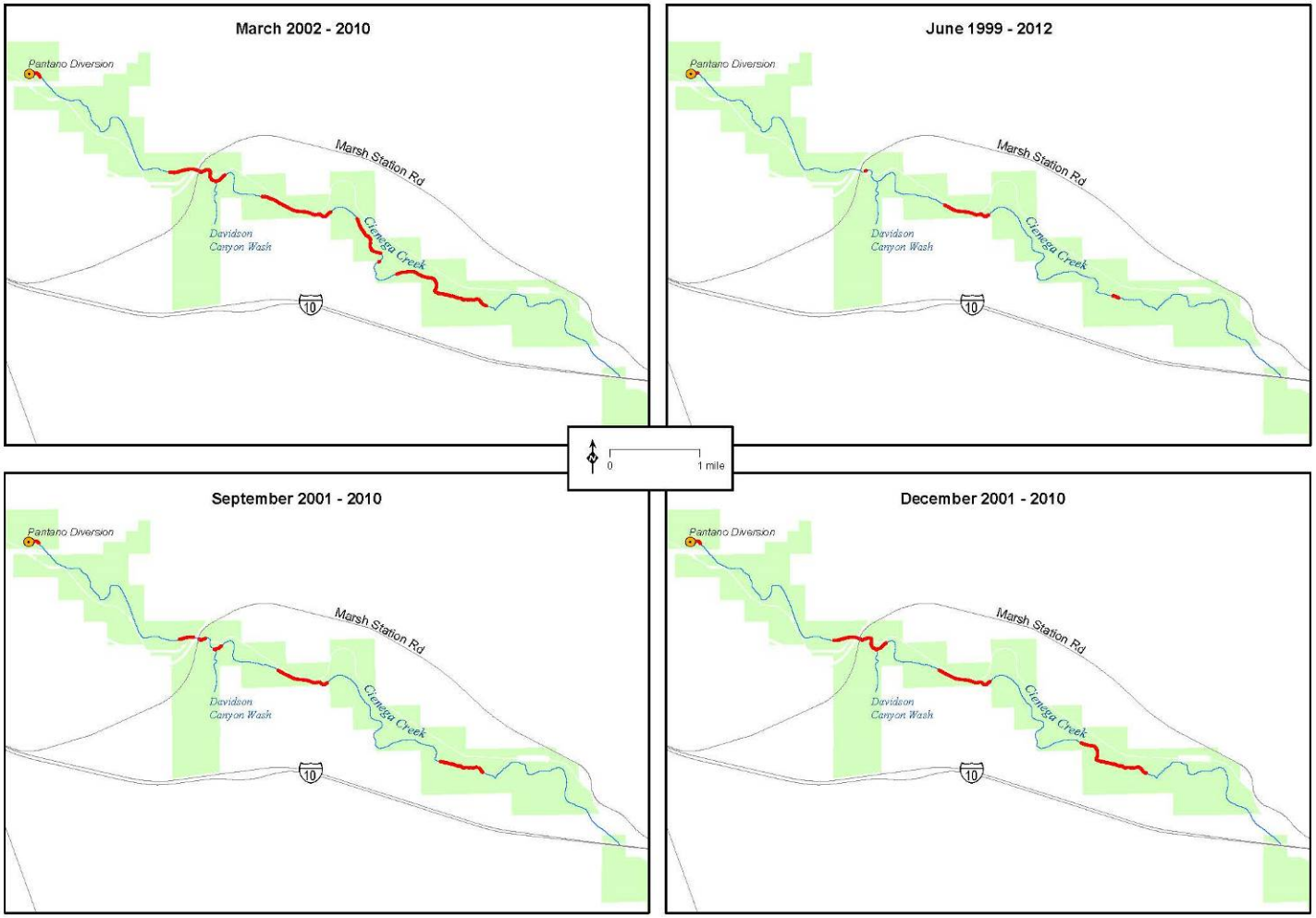


Figure 23. Minimum extent of streamflow at the Cienega Creek Preserve for the four, quarterly sampling events each year, 1999-2012.

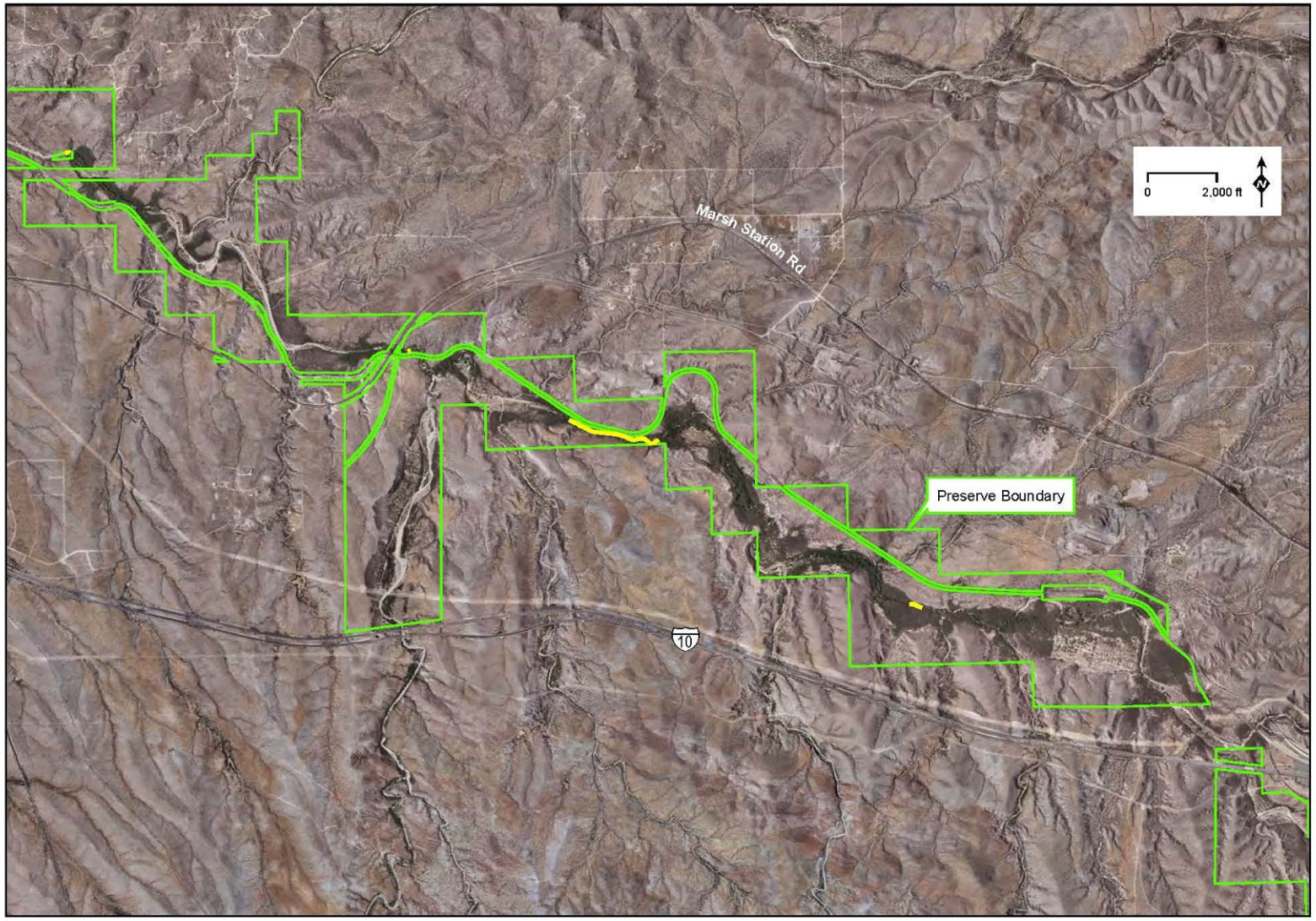


Figure 24. Minimum extent of streamflow at the Cienega Creek Preserve (noted as yellow lines or dots) for all sampling periods combined, 1999-2012.

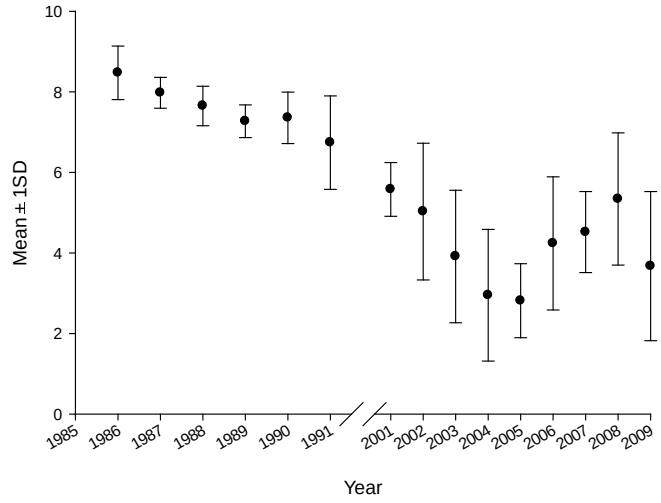


Figure 25. Mean and standard deviation of miles of streamflow for years with at least 4 seasonal measurements, Cienega Creek Natural Preserve. Note both the mean decline and the increase in variability over time.

Influence of Precipitation on Streamflow Extent

Mean streamflow extent was most influenced by year but no other factors (multiple regression, $F_{6,39} = 3.3$, $P = 0.01$, $R^2 = 0.34$; Table 4). Flow extent did not appear to be influenced by rainfall in the one and two months prior to sampling.

Depth to Groundwater

Depth to groundwater in wells declined in all eight wells during the period of record for each well (Figure 26). The decline was most pronounced in the Empirita and Jungle wells and less pronounced in the PS-1 and PN-2 wells, which had the shorted period of record and the most intra-annual variation. Del Lago 1 also had a lot of intra-annual variation, while Empirita and Jungle has less variation (Figure 26).

Table 4. Results of multiple regression analysis on the relationship between surface flow extent other variables thought to influence extent.

Effect	Estimate	F	df	P
Precipitation from 1 month prior	0.19	0.19	1	0.6651
Precipitation from 2 months prior	0.14	0.33	1	0.5705
Year	-0.16	13.42	1	0.0007
Month	-0.05	0.47	1	0.4932
Year*month	-0.0005	<0.01	1	1.0000

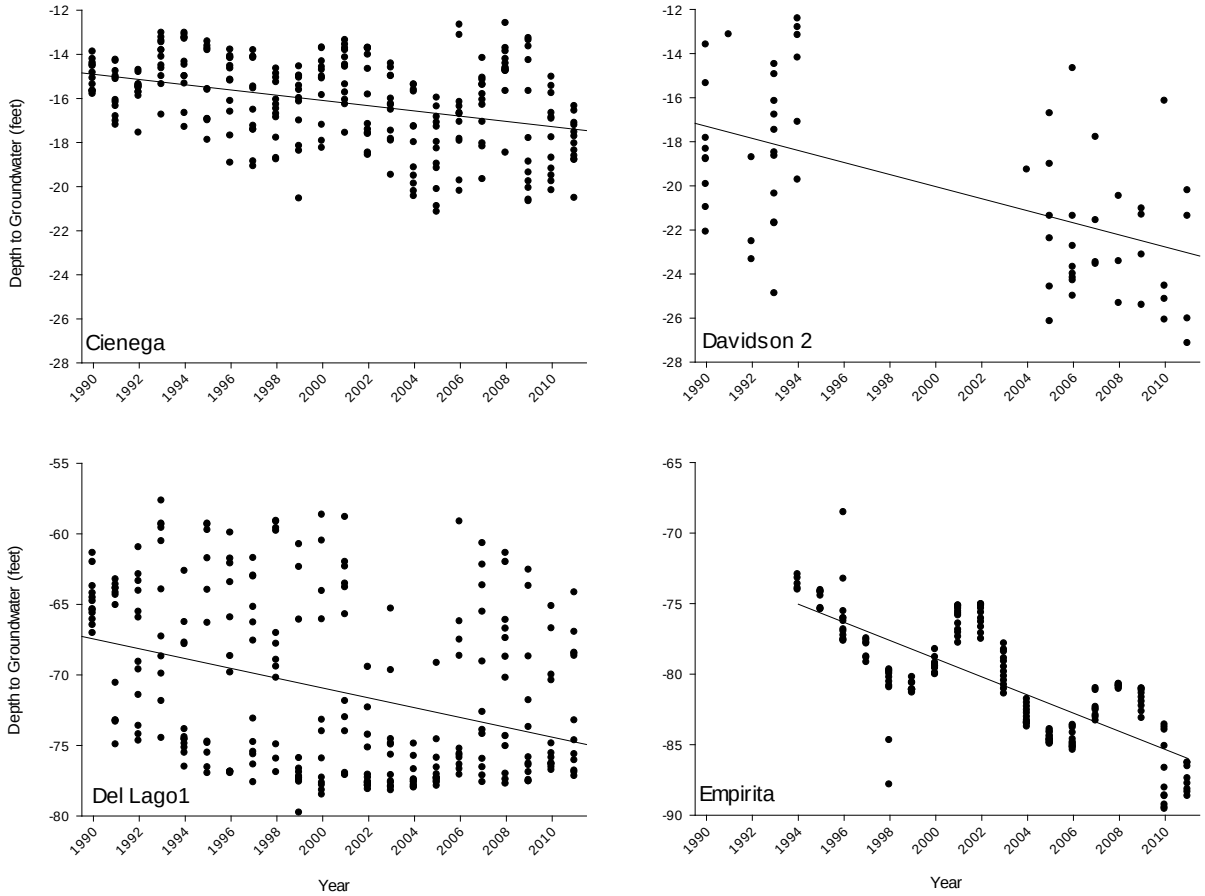


Figure 26. Depth to groundwater from monthly measurement and linear regression analysis by well, Cienega Creek Preserve. Note scale differences in vertical (X) axes.

Total precipitation and lag (in months) did not have high correlation with depth to water measurements (Table 5). Depth to water at the various wells were associated with different explanatory variables (Table 6), but the influence of year was consistently strong (i.e., $P<0.01$) for all but one well. The association between depth to water and precipitation varied among wells.

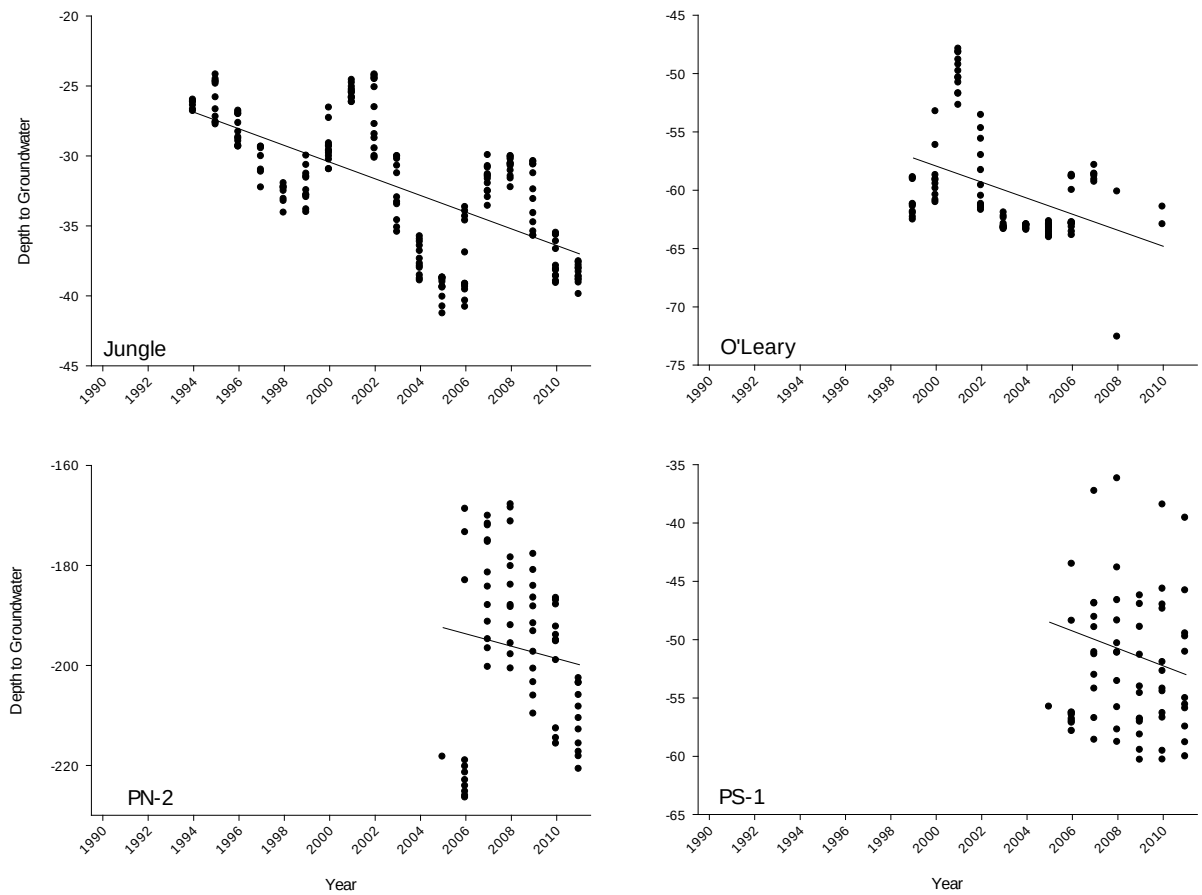


Figure 26, cont.

Table 5. Correlation coefficients between various measures of flow (Pantano Gage) and precipitation and groundwater levels at wells within or near to the Cienega Creek Natural Preserve. Data from 1990-2011. Correlations in bold show a ≥50% correlation. "Totals from previous number of months" is a measure of past precipitation. For example, "2" is the sum of the rainfall from previous two months.

	Flow at the Pantano Gage		Precipitation					
			Lag (Months)			Totals from previous number of months		
Well	1 month prior	2 months prior	1	2	3	1	2	3
Cienega	0.45	0.31	0.22	0.12	-0.02	0.22	0.21	0.16
Davidson #2	**0.61**	**0.54**	0.48	**0.50**	0.09	0.48	**0.58**	**0.57**
Del Lago #1	**0.60**	0.41	0.49	0.34	0.10	0.49	0.52	0.47
Empirita 2	0.18	0.18	0.01	-0.02	0.00	0.01	0.00	0.00
Jungle Well	0.27	0.27	0.06	0.06	0.04	0.06	0.08	0.08
O'Leary Windmill	0.15	0.18	0.11	0.07	0.10	0.11	0.11	0.14
PN-2	0.31	0.42	0.05	0.32	0.48	0.05	0.23	0.43
PS-1	**0.70**	0.47	0.71	**0.59**	0.12	**0.71**	**0.82**	**0.74**

Table 6. Results of multiple regression analysis on the relationship between depth to groundwater and other variables thought to influence that parameter.

Well	Effect	Estimate	Model R2	F	P
Cienega			0.37	29.7	<0.001
	Year	-0.11		54.4	<.0001
	Month	-0.24		71.2	<.0001
	Year*month	-0.006		2.9	0.13
	Precipitation from 1 month prior	0.11		0.5	0.45
	Precipitation from 2 months prior	0.294		9.9	0.001
Davidson 2			0.68	23.6	<0.0001
	Year	-0.25		36.7	<0.0001
	Month	-0.20		4.4	0.04
	Year*month	0.05		13.4	0.0005
	Precipitation from 1 month prior	-0.12		0.1	0.78
	Precipitation from 2 months prior	1.14		22.4	<.0001
Del Lago#1			0.42	36.7	<0.0001
	Year	-0.31		41.7	<.0001
	Month	-0.35		15.0	0.0001
	Year*month	0.02		2.1	0.1521
	Precipitation from 1 month prior	0.96		4.6	0.0332
	Precipitation from 2 months prior	1.47		25.7	<.0001
Empirita2			0.59	50.1	<0.0001
	Year	-0.65		248.33	<.0001
	Month	-0.02		0.13	0.7170
	Year*month	-0.01		0.01	0.9829
	Precipitation from 1 month prior	-0.03		0.01	0.9222
	Precipitation from 2 months prior	-0.22		1.22	0.2708
Jungle			0.42	28.4	<0.0001
	Year	-0.60		134.17	<.0001
	Month	-0.15		3.47	0.0638
	Year*month	-0.01		0.33	0.5633
	Precipitation from 1 month prior	-0.04		0.01	0.9094
	Precipitation from 2 months prior	0.20		0.62	0.4329
O'Leary			0.12	2.8	0.02
	Year	-1.60		11.66	0.0009
	Month	-0.07		0.04	0.8514
	Year*month	0.14		1.04	0.3109
	Precipitation from 1 month prior	0.24		0.02	0.8998
	Precipitation from 2 months prior	0.50		0.16	0.6917
PN-2			0.15	2.5	0.04
	Year	-1.18		1.16	0.2849
	Month	0.53		0.8	0.3614
	Year*month	-0.48		2.36	0.1294
	Precipitation from 1 month prior	-4.98		3.3	0.0732
	Precipitation from 2 months prior	4.180		5.62	0.0207
PS-1			0.71	33.2	<0.0001
	Year	-0.70		5.74	0.0194
	Month	-0.16		1.04	0.3118
	Year*month	-0.07		0.64	0.4277
	Precipitation from 1 month prior	1.05		2.01	0.1607
	Precipitation from 2 months prior	3.08		41.84	<.0001

Palmer Drought Severity Index and Regional Rainfall patterns

Pima County is in an increasingly severe drought (Figure 27). From 2000-2011, there have been only 3 years with conditions that would be considered not to be drought, while 7 years during this time have been in moderate to extreme drought. Looking at a longer view, there have been long-term droughts in the past century, most notably from the late 1930s through the late 1950s (Figure 28).

Precipitation in the Tucson basin from 1970s through 2011 also shows that drought conditions of the last 10 years have been below the long-term average (Figure 29).

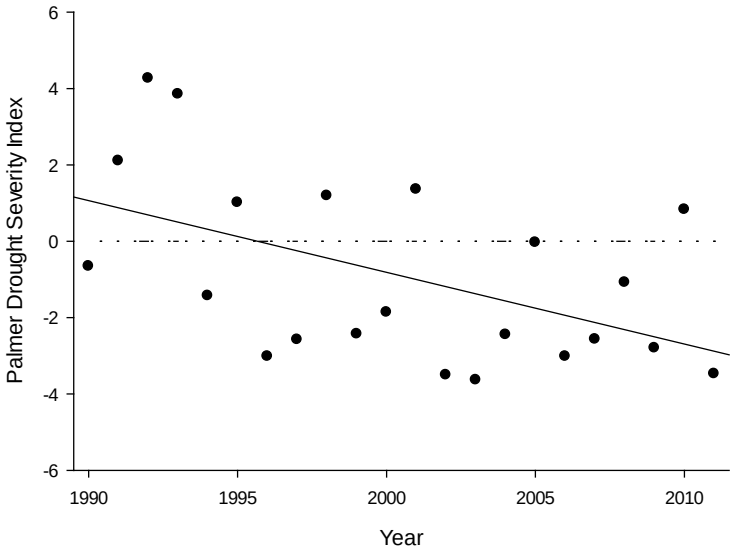


Figure 27. Palmer Drought Severity Index for Pima County, 1990-2011, showing an increase in drought severity in the region, as indicated by the linear trend line. Values below the dashed line indicate drought conditions.

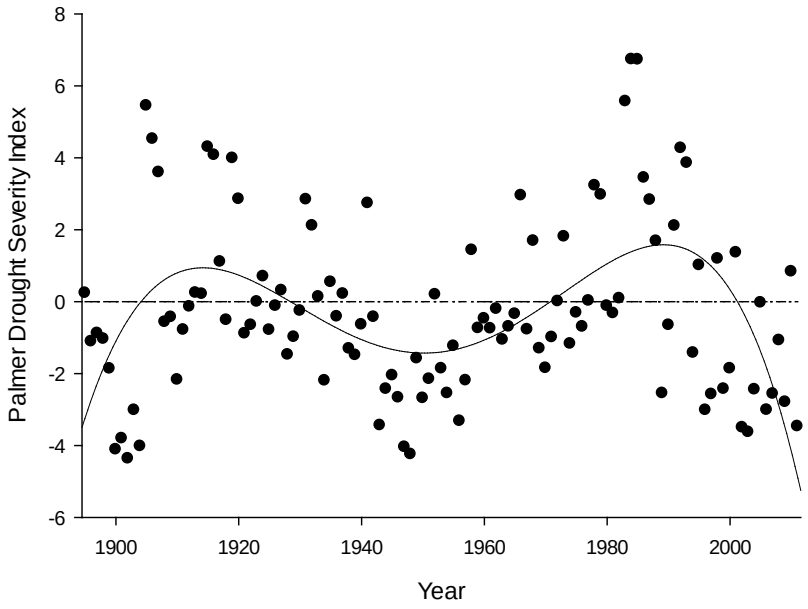


Figure 28. Palmer Drought Severity Index for Pima County, 1891-2011, showing the cyclical nature of droughts in our region. Values below the dashed line indicate drought conditions. Solid line is a 6th order polynomial that maximizes the variation in the data.

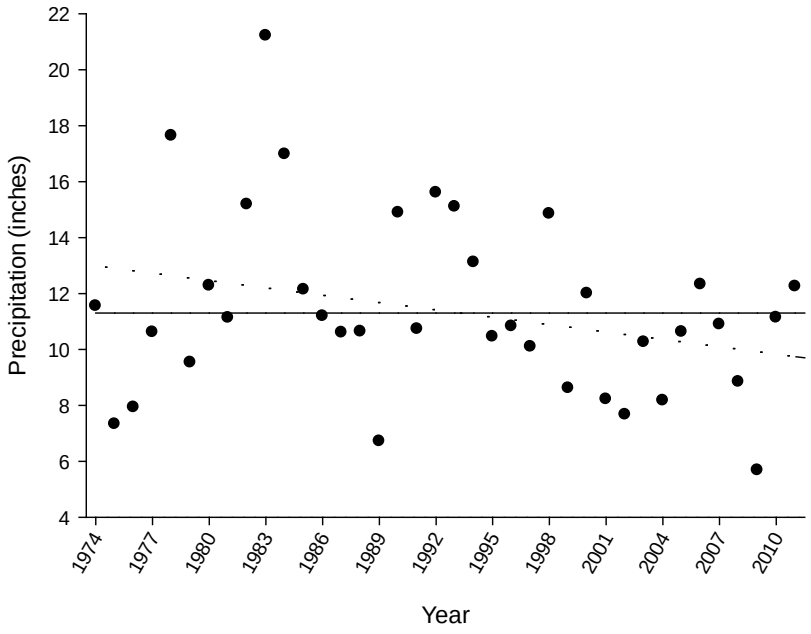


Figure 29. Precipitation measured at the Tucson airport also shows a decreasing trend over time, 1973-2011 (dashed line). Solid line is the long-term average (1891-2012).

Discussion

Summary of Trends and Regional Context

All water resources within the Preserve that are summarized in this report showed a decline over time. Streamflow and discharge were among the parameters that showed the greatest decline; between 1990 and 2011, the mean value of these two measures declined by 68% (Figure 12) and 83% (Figures 16 and 17), respectively. Similarly, the geographic extent of surface water flow decreased from a high of 9.5 miles in the 1980s to a low of 1.1 miles in 2011 (Figure 21), a decline of 88% during that time. The change was less pronounced, but still significant, from 1999-2011 during which time it declined by 63%. Changes in depth to groundwater varied among wells, but declines were as much as 44% (Jungle Well from 1994-2011; Figure 26).

Identifying the underlying cause(s) of the observed declines in these critical water resources is beyond both the scope of this report and the data themselves, but it is instructive to speculate on likely causes and identify key uncertainties. This section discusses the host of potential causes for this decline, including the hydrogeological setting, recent history of downcutting, followed by discussions of the input (precipitation) and output (evapotranspiration and groundwater pumping). By comparing data associated with each of these input and outputs, a narrative develops that may help explain the changes to the invaluable water resources of the Preserve.

The underlying hydrogeology of the Preserve and watershed is critical starting place for the discussion of observed changes. The area in and around the Preserve has been the subject of a number of hydrology and geological studies (Kennard et. al. 1988; Fonseca 1993; Ellett 1994; Chong-Diaz 1995; Pima Association of Governments 2003). Four hydrogeologic units occur in the Cienega Creek basin: younger alluvium, basin-fill alluvium, Pantano Formation, and bedrock complex (Kennard et al. 1988). The younger alluvium is up to 105 feet thick, consisting of unconsolidated silt, sand and gravel and found along the geologic flood plain of Cienega Creek and its tributaries, thereby forming the major aquifer under the Preserve. The younger alluvium has higher transmissivity and specific yield than the basin-fill alluvium, which is found upstream of the Preserve. The basin fill alluvium consists of 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 (Kennard et al. 1988).

Also important to understand is how the aquifer recharges and discharges. Groundwater recharge occurs primarily along the slopes of the surrounding mountains, and from infiltration of ephemeral flows along Cienega Creek and its tributaries (Figure 30). Baseflows at the Preserve are derived from upstream basin groundwater (Grahn, 1995) and present themselves at locations with shallow bedrock, where groundwater is forced to the surface, creating perennial streamflow (Chong-Diaz 1995). This is particularly true in areas where the

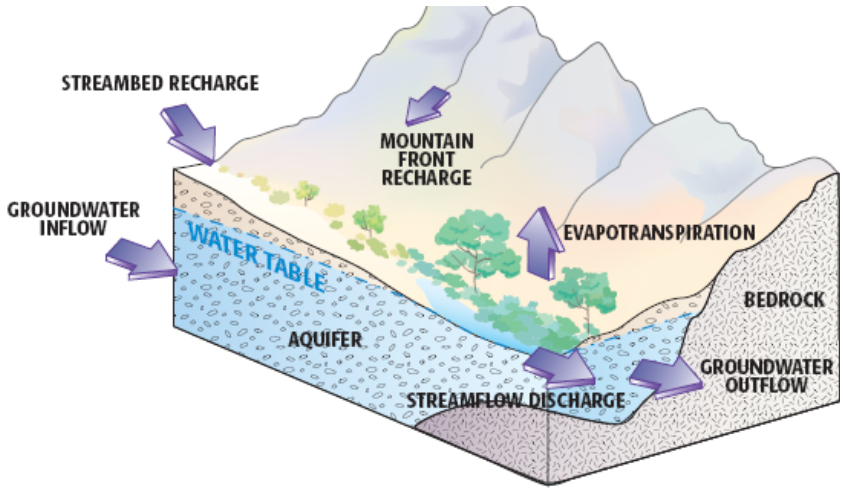


Figure 30. Sources of water inflow and outflow to a basin. A high water table can support streamflow discharge, but less recharge can lead to a lower water table and subsequently less streamflow. Figure from Fonseca (2008).

alluvium is restricted to relatively narrow bands (see Appendix E) bordered by consolidated rock units (Bisbee Formation, lower Pantano formation, the andesite, and the Paleozoic limestone). An exception to this can be found near the Tilted Beds site, which has a broader floodplain (Appendix E), a fact that may help explain why this site has only intermittent surface flow (Figure 11). Many of the areas where surface flow terminates are associated with fault zones with transitions from highly consolidated rocks to less well consolidated rocks (Pima Association of Governments 2003), though it appears that the fault zones are not contributing new sources of water to Cienega Creek from deeper within the earth. A number of questions about the role of the underlying geology of the area remain unanswered and doing so could lead to a better understanding of the influences of the geology on surface and groundwater resources (see PAG 2003 for more information).

It is also important to note that what is now Cienega Creek at the Preserve was historically a large cienega system with year-round water and marshy conditions. As happened in many other cienegas in the region, overgrazing and subsequent loss of vegetative cover and groundwater pumping have led to massive arroyo downcutting (Hendrickson and Minckley 1984; Turner et. al. 2003). The result is that the current channel elevation of Cienega Creek is far below that of its position of approximately 150 years ago (see Figure 31).

Fonseca (1990) estimated that a minimum of 4 million tons of sediment was removed from the Preserve between the 1880s and the mid 1930s; historically this sediment would have acted to capture and release water from the shallow aquifer. Downcutting of the stream channel started again in 1999 and accelerated from 2001-2009 (Pima Association of Governments 2010). This event was caused by a lowering of the groundwater table with the erosion taking place because the system was attempting to find an equilibrium. These successive downcutting events have had an important impact on the flow and length of flow within the Cienega Creek. However, the headcutting that took place from 1999-2009 cannot explain the changes to surface water resources observed during this study (Figures 12, 21), in part because that headcutting actually restored base flow in some parts of the creek

(though dried others). The headcutting did, however, reduce the long-term storage capacity of the shallow groundwater aquifer by washing sediments downstream.

Figure 31. The current level of the creek sits below its historic floodplain in the Cienega Creek Natural Preserve, 2012. Note the two people in the foreground for scale.

Streambed aggradation and degradation will be an important attribute to monitor over time. As noted, streambed degradation has been a conspicuous feature at the Preserve, but it has not been uniform. In fact, there are areas of aggradation downstream of the headcut area that threaten the few, deep water pools that are critical to the persistence of Gila chub, in particular. Clearly aggradation and degradation are important and historically have been difficult to monitor without considerable field effort. Now, airborne LiDAR technologies are providing a new and efficient tool for measuring aggradation and degradation along entire stretches of rivers, thereby giving new possibilities for monitoring this change. In fact, Tyson Swetnam at the University of Arizona is currently analyzing LiDAR data from the Preserve for aggradation and degradation as well as canopy cover.

Precipitation. Though past land-use history and the underlying geology of an area provide a foundation of understanding current conditions in water resources of Cienega Creek, clearly precipitation is a key determinant of trends in these resources, and this report specifically targeted the role of precipitation in understanding the trends in many of the water resources of interest (Tables 3-6). With the exception of a few years with above-average rainfall, the 1990s and especially the 2000s in southern Arizona were historically very dry (Figures 7, 9, 28, 29). Precipitation totals have been especially low since 2002 compared to the long-term mean within the Cienega watershed and Tucson (Figure 7). In fact, in seven of the years between 2002 and 2011 recorded precipitation totals were below the long-term average, but the decline in the key measures of water resources at the Cienega Creek Preserve (i.e., flow, extent, groundwater) do not directly follow trends in precipitation. For example, comparing the mean annual flow extent between 1990 and 2011 shows a 50% decline (Figure 21), but comparing precipitation between those two years shows a 16% decline (Figure 29). Clearly precipitation plays an important role in determining the condition of water resources in Cienega Creek, but other factors are also at play.

The spatial pattern and seasonal timing of precipitation falling within the watershed may be important to consider, and though there are some among-site differences in these measures

based on their position within the watershed, among-site precipitation totals did not change from 1993-2011. There were, of course, seasonal differences in precipitation with a greater percentage of precipitation falling during the summer rather than the winter season (Figure 8). This was true for all seven precipitation gages, and though there was a change in the mean seasonal precipitation (averaged among sites; Figure 10), these changes were not statistically significant. If spatial changes were seen, then runoff and infiltration characteristics of certain watersheds that contribute to Cienega Creek might partially explain changes detailed in this report. (It is important to note that changes in the spatial patterns of precipitation may not have been picked up by this study; the precipitation gages were not spread about the entire watershed). This finding of insignificance is important, because runoff and infiltration vary among seasons. More research is needed to determine the relative contributions of summer and winter precipitation to the shallow aquifer within Cienega Creek.

Patterns in change in baseflow and discharge are some of the most important and interesting patterns in the data summarized in this report (Figures 11-19). These data show both statistically and environmentally significant declines over time, but it is not the same when compared by months (Figures 13, 19). Those months that represent the monsoon (July, August, and September) do not show statistically significant declines for baseflow (Figure 13). The August and September flow measurements are also highly variable, indicating that they are likely responding to high rainfall events that can temporarily increase baseflow, but which may not have lasting impacts on baseflow. Baseflow conditions in June are perhaps the most important to monitor because they represent the time of year when water is most scarce and the demands on the water resource (by way of groundwater pumping and evapotranspiration) the greatest. June shows a declining trend over time with very little variation that is not explained by the linear trend (Figures 13, 19). Streamflow extent is also most restricted in June, a sampling period that shows a steady and rapidly declining trend (Figure 22). Further discussion about this trend can be found in the section about the ecological significance of the observed changes.

Streamflow extent is an important monitoring parameter at the Preserve. This monitoring is also undertaken at other sites in the Cienega watershed and at other rivers and streams in southeastern Arizona. In closest proximity to the Preserve is the effort along Cienega Creek at Las Cienega National Conservation Area, which is upstream of the Preserve. There, June mapping efforts have shown a marked decrease in flow extent, from 9.5 miles in 1990 to a low of 4.8 miles in 2012 (Jeff Simms, *unpublished data*), a 50% reduction. However, from 2006-2011, a period that is directly comparable with data from this report, the extent of surface water actually increased, whereas it decreased markedly at the Cienega Creek Natural Preserve (Figure 32). On the nearby San Pedro River, Turner and Richter (2011) summarize 12 years of data from along approximately 80 km of the river and found no statistically significant declines during that time. The drought conditions that were experienced in the Cienega watershed were also taking place in the San Pedro River watershed, the next large watershed to the east of Cienega (Figure 33).

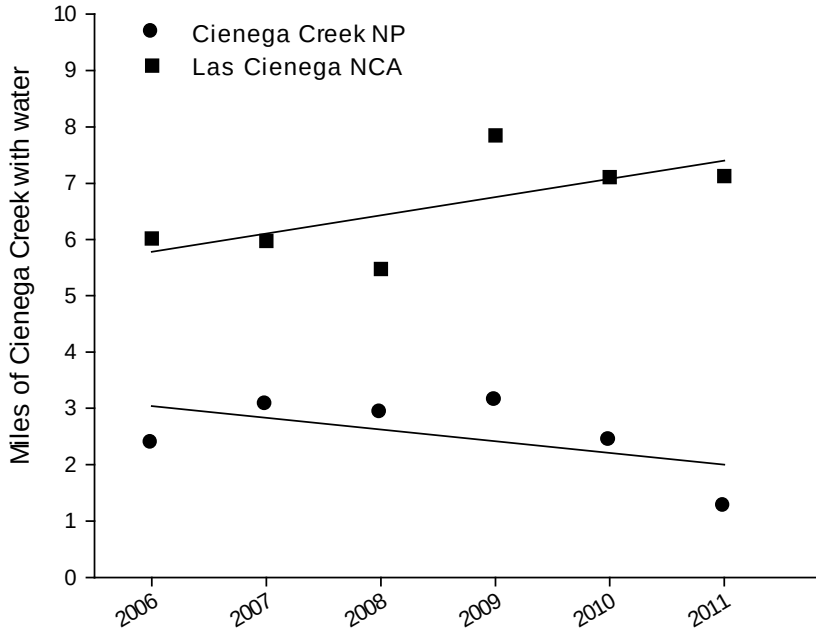


Figure 32. Length of streamflow at the Cienega Creek Natural Preserve (NP) and Las Cienegas National Conservation Area (NCA), as measured in June of each year.

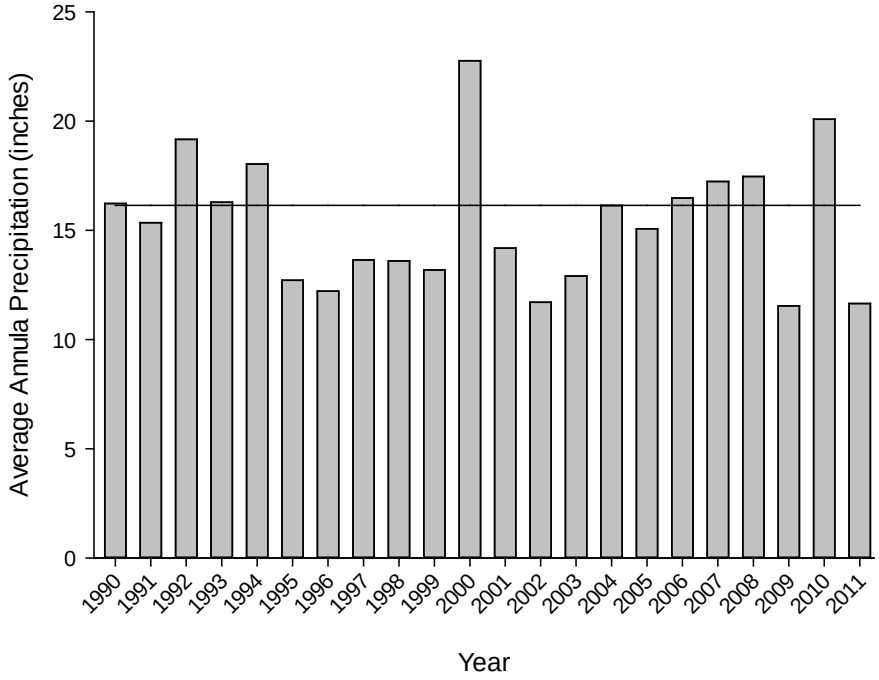


Figure 33. Annual precipitation averaged among 4 sites on the San Pedro National Conservation Area, east of the Preserve (Data obtained from Russ Scott, USDA Agricultural Research Service). Solid line is the average from 1971-2000.

Precipitation clearly plays a critical role in determining stream discharge (Table 3), streamflow extent (Table 4), and groundwater levels (Tables 5,6). Yet, the precipitous decline in these water parameters cannot solely be attributed to changes in precipitation totals . The fact that surface water resources (and to a lesser extent, groundwater resources) of lower Cienega Creek declined more precipitously than either the upper Cienega Creek or the San Pedro River bolsters this perspective.

The Role of Evapotranspiration. Large riparian trees can use a significant amount of water to support photosynthesis; a process known as evapotranspiration. A large cottonwood tree can use as much as 200 gallons/day, so it stands to reason that greater evapotranspiration rates from the Preserve's gallery riparian forest may be responsible for a reduction of the streamflow extent and volume. Early results from a study by Tyson Swetnam (*unpublished data*) does not lend strong support to this hypothesis, at least in regards to changes observed in the last decade (Figure 34). It is important to note that prior to the establishment of the Preserve there was extensive cattle grazing on the site, but once cattle were removed from the system, vegetation height and volume increased significantly (see Figure 2) and likely plateaued in the early 2000s (*unpublished data*). Vegetation often responds positively to removal of cattle (Krueper et. al. 2003), but since 2005 there has only been a slight increase in the extent of cottonwood canopies in the Preserve (Figure 34), though this analysis does not address the density of vegetation within the canopy. It is also important to note that the extent and vigor of mesquite trees has declined during this time. Another line of evidence that does not support the evapotranspiration hypothesis can be found in the fact that both the extent of streamflow and flow volume also declined in December (Figures 13, 19, 22), a month when there would be no evapotranspiration. However, the decline in streamflow extent (Figure 22) and discharge (Figure 19) was greatest during the June sample period, a time when evapotranspiration is probably the greatest. Clearly more research is needed to understand the role of evapotranspiration in the water budget of Preserve.

Groundwater Pumping. Another key factor to consider in regards to the water resources at the Preserve is the pumping of shallow groundwater. Identifying the quantity of water withdrawn by wells can be very difficult to determine because pumping records do not exist for any exempt wells or for non-exempt wells outside of Active Management Areas (only portions of the Cienega Creek watershed is within the Tucson Active Management Area; therefore records are incomplete for non-exempt wells). Nevertheless, some data are available and they show an increase in both the number of new wells drilled (Figures 35, 36) and amount of pumping near to the Preserve (Figure 37). Both of these measures have increased significantly since 2000.

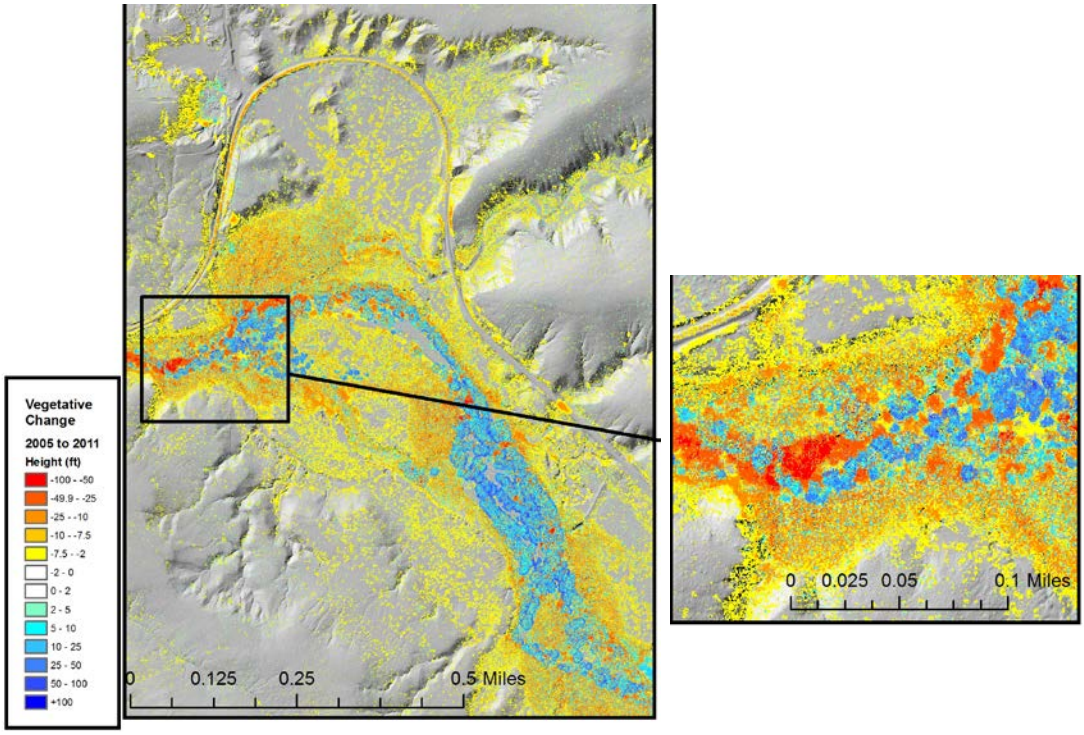


Figure 34. Change in vegetation between 2005 and 2011 at the horseshoe area of the Cienega Creek Natural Preserve. Most of the vegetation away from the active channel had declined, whereas there has been a slight but not significant increase in cottonwood/willow increase along the active channel. Note that much of the dark blue is because of a growth on the outside of the canopies. Zoomed in area is from the loss of cottonwood and mesquite from the recent headcut. Unpublished data from Tyson Swetnam.

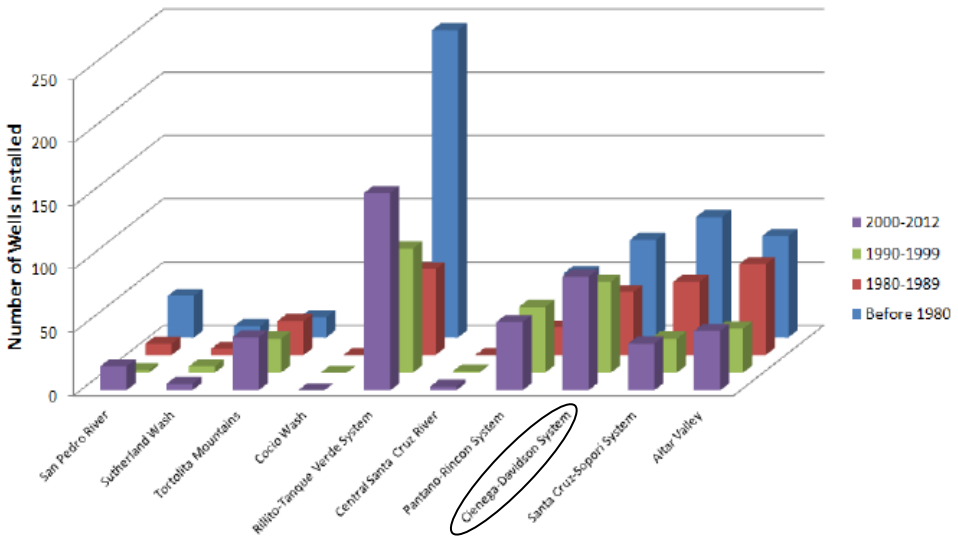


Figure 35. The number of exempt wells drilled within 1 mile of groundwater basins of eastern Pima County. Note that the Cienega-Davidson basin had the second-highest number of wells drilled from 2000-2012. Data and figure from Pima Association of Governments (2012).

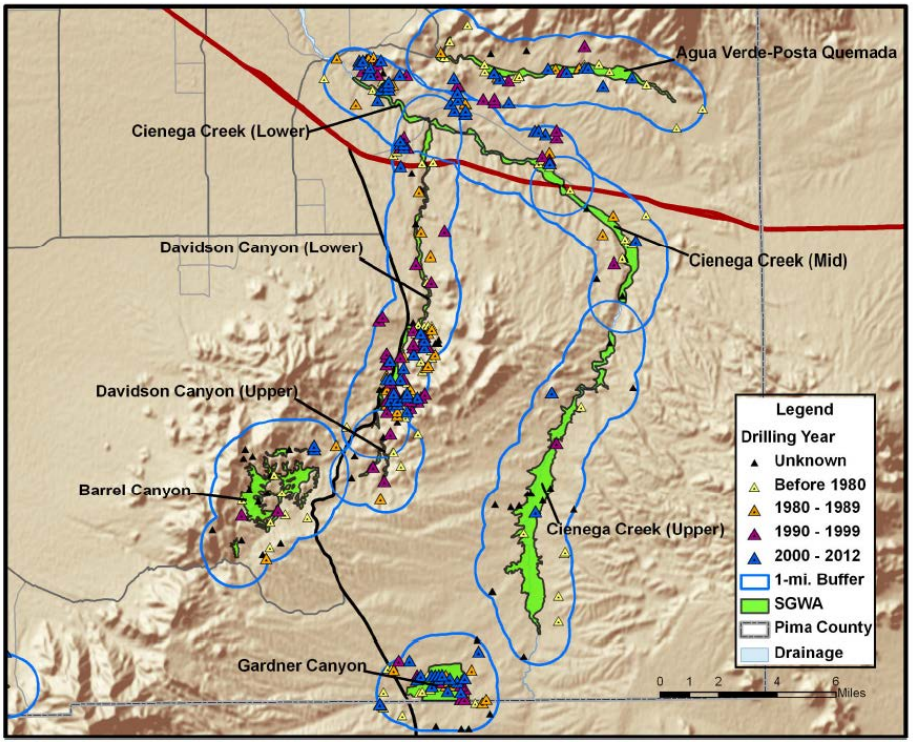


Figure 36. Wells within the shallow groundwater areas (SWGA; in green) of the Cienega-Davidson basin. Cienega Creek Natural Preserve is located in the area shown as Cienega Creek (Lower). Note the relatively narrow shallow groundwater area in the preserve compared to the areas shown as Cienega Creek (Upper); which is located at Las Cienega National Conservation Area. Figure from Pima Association of Governments (2012).

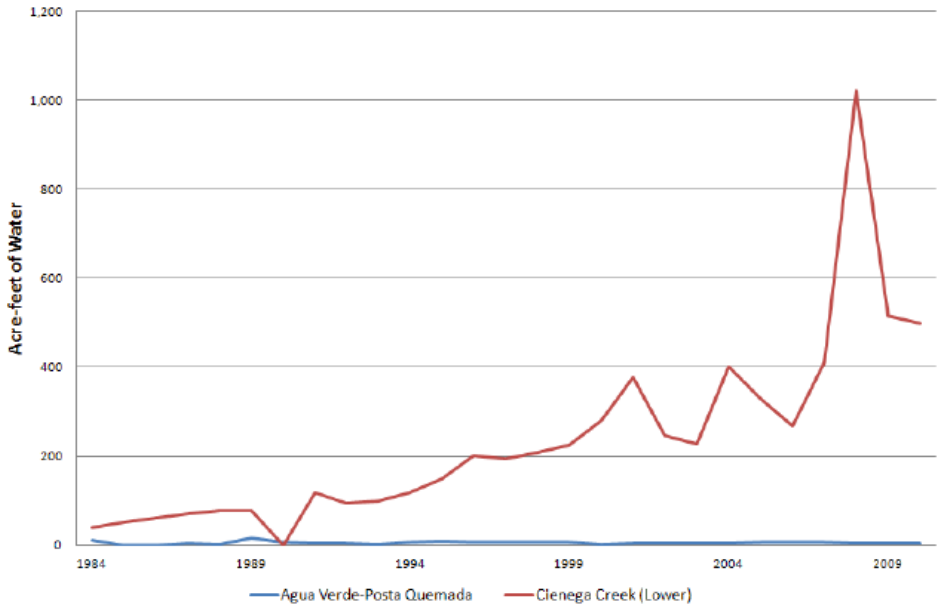


Figure 37. Total water withdrawals from non-exempt wells in the Cienega-Davidson shallow groundwater area. Data and figure from Pima Association of Governments (2012).

Data collected at the Preserve was not collected to specifically investigate direct, cause-and-effect relationship between groundwater pumping and a decline in measures such as streamflow length and depth to water (Figure 26). As noted earlier, a decline in precipitation has played a role in the decline of these resources, but the increased groundwater pumping cannot be eliminated as a key contributor to the decline of water resources in the Preserve. Given the relatively small size of the shallow groundwater aquifer within the Preserve (see Figure 36), it is particularly vulnerable to the influence of groundwater pumping.

Ecological Significance of Declining Water Resources

The decline of surface water and groundwater resources on the Preserve is a cause for concern in its own right, but changes in those resources also have and will have cascading impact on the biota of the Preserve. This will be especially true of the aquatic animals and plants that are now spatially restricted during the June survey periods (Figures 22, 23; Appendix B). Chief among the species that might experience a decline are the fishes and lowland leopard frogs that currently inhabit the Preserve. The presence of the two of the three species of fishes now present at the Preserve (Gila topminnow and Gila chub) is a relatively recent occurrence (though records are incomplete prior to the 1980s); presumably these species were washed down from the upper reaches of Cienega Creek during floods, but have become established because there is suitable habitat at the preserve. Despite their relatively recent tenure in the Preserve, they almost certainly occurred there historically and their continued presence requires perennial water flow. The impact of the reduced flow and extent at the Preserve has not been studied but further declines of surface flow and extent will almost certainly impact the fish, particularly in the historically dry May and June period. The Arizona Game and Fish Department recently began annual fish monitoring at two sites within the Preserve (Marsh et. al. 2009, 2010; Clarkson et. al. 2011). Surveys in 2012 failed to find Gila chub in the creek, and though others have reported seeing it (Don Carter, *personal communication, December 2012*), it is a species that lives in relatively deep pools that form in the few areas of bedrock intrusion near the stream channel. These are also the areas downstream of the recent headcutting, an event that has washed considerable sediment into these deeper pools. The chub's habitat appears to have declined as a result. Lowland leopard frogs also require open water and though they have never been very abundant at the Preserve, their numbers also have appeared to decline in recent years (Dennis Caldwell, *unpublished data*).

Aquatic or semi-aquatic animals are not the only group that appears to have declined or may decline in the future. The decline in base flow also impairs hydrological function of the system by increasing depth to groundwater, which in turn, affects riparian vegetation that relies on groundwater (Figure 38). Evidence of this can be found in the mesquite bosque vegetation community that borders the mesic riparian vegetation along the creek margins. The extent and vigor of this species appears to be on the decline.

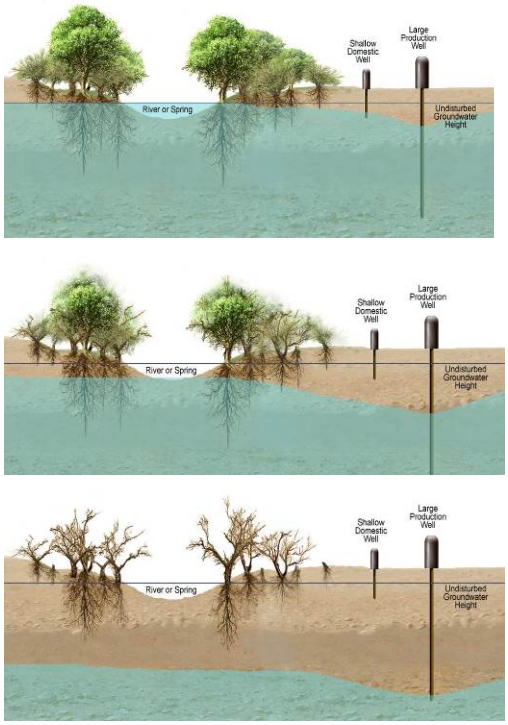


Figure 38. Effects of groundwater decline upon riparian vegetation, from climate change and/or groundwater pumping. The first effects include reduced canopy foliage and reduced herbaceous vegetation diversity and cover. Loss of base flows to stream is shown in second panel, followed by death of characteristic woody riparian trees as groundwater declines below the root zone. Illustration by Bill Singleton and Julia Fonseca originally appeared in Fonseca (2008).

Variability and Thresholds

The *variability* of surface water resources, particularly in the last few years of the monitoring effort (Figures 12, 13, 16, 19) also deserves attention. Recent research has shown that ecosystem dynamics become more variable prior to changing from one dominant state to another (also known as a regime shift; Oborny et. al. 2005; Carpenter and Brock 2006). Whether the variability of extent of streamflow, in particular, signals a future regime shift at the Preserve remains to be seen, but it is interesting to note that this variability began to occur around the time that the headcut began to progress upstream.

The concept of variability also relates to thresholds, which, when crossed, can change the system from one state to another. Of particular interest at the Preserve is the depth to shallow groundwater, which controls the type and extent of riparian vegetation (Figure 39). Fremont cottonwood and willow trees, for example, are very sensitive to declines in groundwater levels and when depth to water consistently exceeds approximately 5 m, these species begin to decline in vigor and may die out altogether (Figure 40).

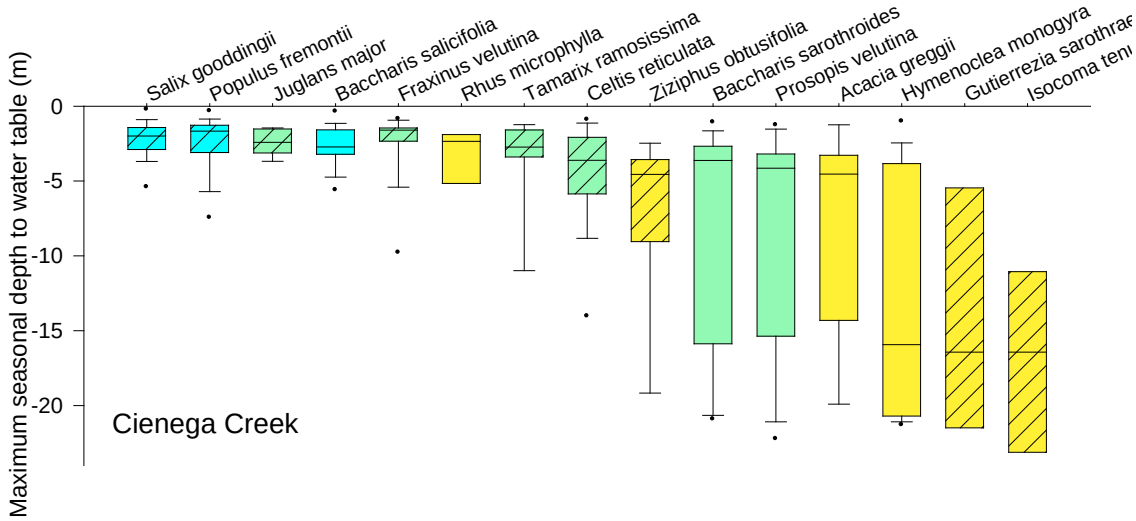


Figure 39. Depth-to-water thresholds for plant species at the Cienega Creek Natural Preserve. Cottonwood (*Populus fremontii*) and willow (*Salix goodingii*) have among the lowest thresholds for depth to water. If water levels drop much further than these minimums, stress or death can result. Note that velvet mesquite (*Prosopis velutina*) has a much greater tolerance, but it occurs away from the shallow groundwater aquifer of the Preserve, where well depths have declined (see Figure 26). Mesquite trees has similarly declined in a number of areas (see Figure 34).

Figure 40. Many cottonwood trees at the Cienega Creek Natural Preserve are showing signs of drought stress. Note the thin canopies of many of the trees. July 2013.

Tamarisk trees, an invasive, non-native species, may be an indicator of a regime shift and this species has increased in abundance in recent years. Though recent control efforts have been successful, the potential for this species to gain a greater foothold in the Preserve is significant and—as we see with the depth to groundwater data (Figure 26)—a highly fluctuating shallow groundwater table may be an important early warning sign of such change.

A Look to the Future

Land use within the watershed. The Preserve is one of the most ecologically important areas of southern Arizona, which results from the water resources that are highlighted in this report. The fact of the Preserve's close proximity to Tucson make it almost unique among areas of similar ecological importance, but development in close proximity to ecological sensitive areas has historically not fared well for the latter. The area in and around the Preserve has historically been the focus of development (particularly in the downstream area of Vail), which has increased significantly, especially in the late decade. Development pressures will only increase in the coming decades as more and more people continue to move to the Tucson region for the jobs and lifestyle. Many of these people will also seek a more exurban or rural place to live (Figure 41). Given the slower—but still steady—pace of development in the area around the Preserve, groundwater pumping will only increase the stress on the water resources of the Preserve (Figure 42). This, coupled with lower rainfall from climate change (see next section), will likely result in less water for natural systems like Cienega Creek.

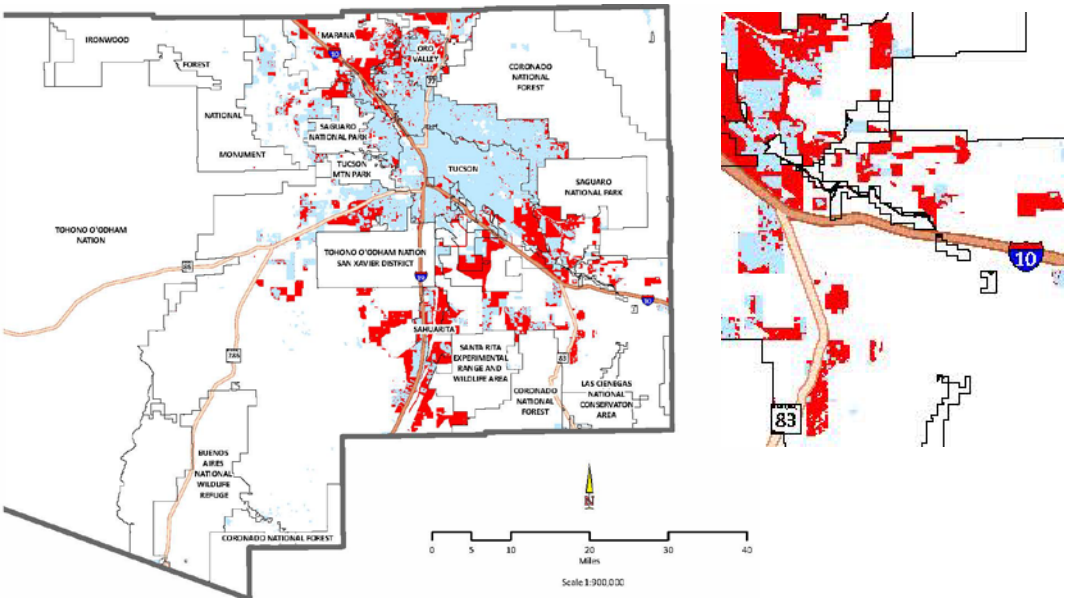


Figure 41. Projected development (red) and existing development (blue) in eastern Pima County over the next 30 years. Image at right is the area around the Preserve. Image from Pima County (2012b).

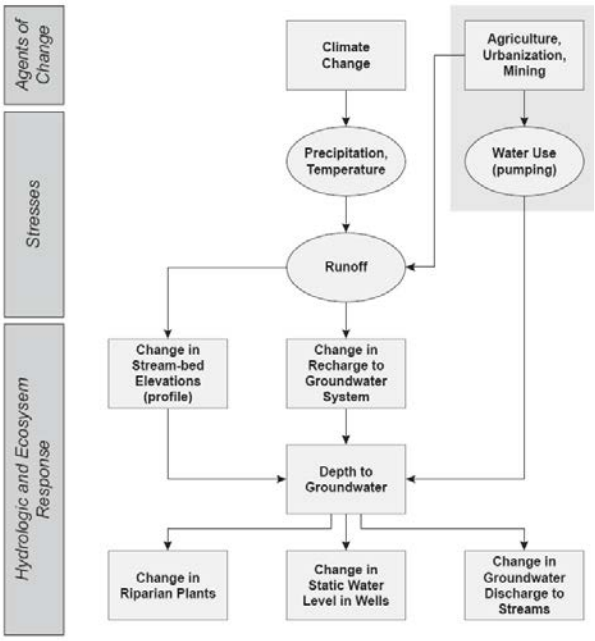


Figure 42. The increased scale and scope of human activities, along with climate change, will put greater and greater pressure on shallow groundwater ecosystems. Figure from Fonseca (2008).

Climate Change. Climate change deserves special attention because its impacts will—if it has not already—impact the water and related resources of the Preserve. During the 20th Century, temperatures on the surface of the earth increased by 0.5°F to 1.1°F, with a dramatic rise in temperatures in the last 50 years (PRISM Group 2007). Models of temperature increases in Arizona have exceeded average global temperature increases by 50% since the 1970s (PRISM Group 2007). Looking forward, worldwide temperatures are predicted to increase between 3.2°F to 7.2°F in the next 100 years (Meehl et. al. 2007). For the southwestern U.S., there is a prediction of a 10-20% reduction in precipitation in the Southwest region in the next 75 years (Christensen et. al. 2007), with most reductions in precipitation during the winter months when circulation patterns over the Pacific Ocean prevent moisture from entering the region through a movement of the storm track to the north. This will leave southern Arizona more arid. Drier conditions are expected to be particularly severe during years when La Niña patterns predominate (Seager et. al. 2007). By contrast, summer monsoons in Pima County result from warm, moist air from the Gulf of Mexico and eastern Pacific, resulting in high-intensity monsoon rains. The processes which bring monsoon rains to southeastern Arizona is not expected to be disrupted in the same way as those processes that affect winter precipitation, though there is considerable uncertainty in these models. Whether the shift in winter versus summer precipitation that occurred at and around the Preserve during the period of record for this study (Figure 43) is

a result of climate change is unknown, but as was indicated earlier, the impact of both a reduction in winter precipitation and increase of steady summer precipitation has important

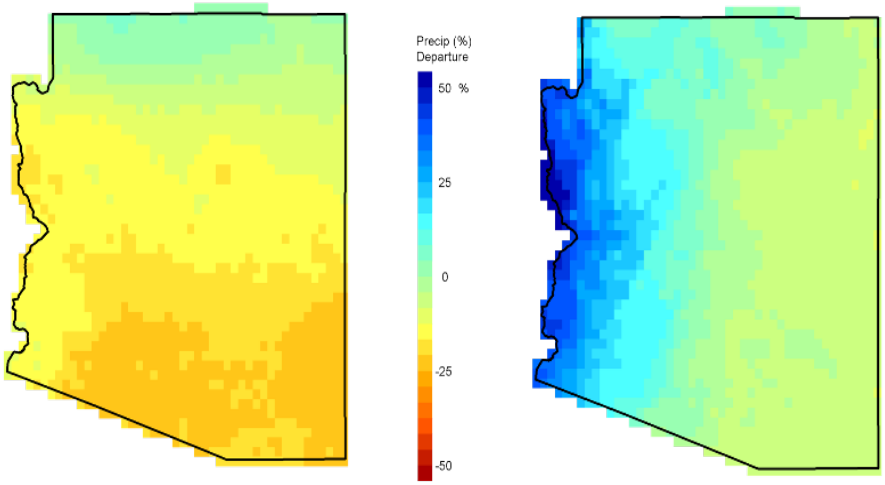


Figure 43. Projected change in precipitation for winter (left) and summer (right) by 2099 under the "business as usual" climate scenario. Projections downscaled by Maurer et al. (2007) for Arizona.

consequences for a host of resources and parameters including groundwater storgage and base flow volume and extent.

Beyond temperature and precipitation impacts will be disruptions to ecological function and structure. For example, much of the water that makes its way into the small aquifer at the Preserve starts further up in the watershed. Here, wildland fire is expected to increase and will hasten transitions to new plant communities, have cascading effects on sensitive plant and animal species (McKenzie et. al. 2004), and impair ecosystem functions. Though fire was once restricted to montane forests, woodlands, and semi-desert grasslands, there is now an increased fire risk in areas such as the Preserve because of the spread of buffelgrass and other invasive species such as brome (Franklin et. al. 2006). Recent efforts to control buffelgrass in the Preserve have been successful, but the rapid, region-wide spread of the species will pose a considerable challenge to managers in the longer term.

Climate change, in combination with other stressors, will also impair watershed function. Warmer and drier soils will generally store more water, thereby increasing the threshold for initiation of runoff, a situation whereby precipitation is in excess of the soil's capacity to store water. However, a combination of more intense summer storms with an increase in urbanization—which can impair the ability of many systems to absorb water (Kepner et. al. 2004)—can lead to cascading impacts, most importantly by changing the structure of stream beds, thereby affecting aquifer recharge. This impairs hydrological function of the system by increasing depth to groundwater, which in turn, affects riparian vegetation that relies on groundwater. All of these changes could have severe consequences for key conservation targets, such as aquatic species (e.g., Parker 2006).

The trees of the mesic riparian cottonwood/willow forests such as at Cienega Creek are susceptible to mortality in the late spring. With a possible reduction in average winter precipitation, dieoff of individuals or entire communities may occur. Acute drought stress on trees in this community was seen throughout the region in the last 10 years, for example along the Santa Cruz River in Santa Cruz County (Amy McCoy, *unpublished data*) Rincon Creek in eastern Pima County (Kirkpatrick et. al. 2007), and on mesquite and cottonwood trees within the Preserve (see Figure 40).

The Rosemont Mine. Another key stress on the water resources of the Preserve will be the Rosemont mine (Figure 44). If approved, the mine will have significant impacts to water quality and quantity in both the short and long-term (Myers 2010; U. S. Forest Service 2011; Pima County 2012a). Short-term impacts include the diversion and impoundment of stormwater, and possible contamination of that water. Long term, the abandoned open pit will act as a groundwater "sink" that will draw groundwater into the pit. Contamination of groundwater is also a likely outcome of the mining operation. Pima County has vigorously opposed the Rosemont operation, in part because of the impacts the mine will have on water resources, impacts that will be revealed far beyond the boundary of the project area. In the case of surface water, these impacts will be to the surface and groundwater inputs of the Preserve.

As part of the mitigation negotiations with the U.S. Army Corps of Engineers, Rosemont Copper has apparently purchased options for water rights that are currently owned by the Rancho del Lago Golf Course. The golf course diverts water from the creek at the del Lago dam (Figure 45) and Rosemont is may allow some of that water to remain the creek channel as mitigation measure for the proposed mine. Allowing these waters to stay within the natural system would clearly be better for the system than piping it to a golf course, but given the large-scale impacts of Rosemont's operations on the water resources upstream of the Preserve, the Company's proposed action may not be effective if Rosemont's mining operation results in a decline in base flows (Pima County 2012a).

Management Options: Linking Data to Opportunity and Constraints

Key water resources at the Cienega Creek Preserve are on the decline. Whether these declines are temporary or will be reversed naturally, only time will tell. However, given the current trajectory of these resources; the ecological and hydrogeological history of the Preserve; and the coming threats of development, mining, and climate change, one could be forgiven if she/he were pessimistic about the future of water and associated resources at the Preserve. Among the many questions being asked about the future, perhaps the most important is: what can we do about the current situation to stop it from getting worse? Answers to that question might range from doing nothing to significant intervention. The most prudent and achievable answer probably lies somewhere in the middle.

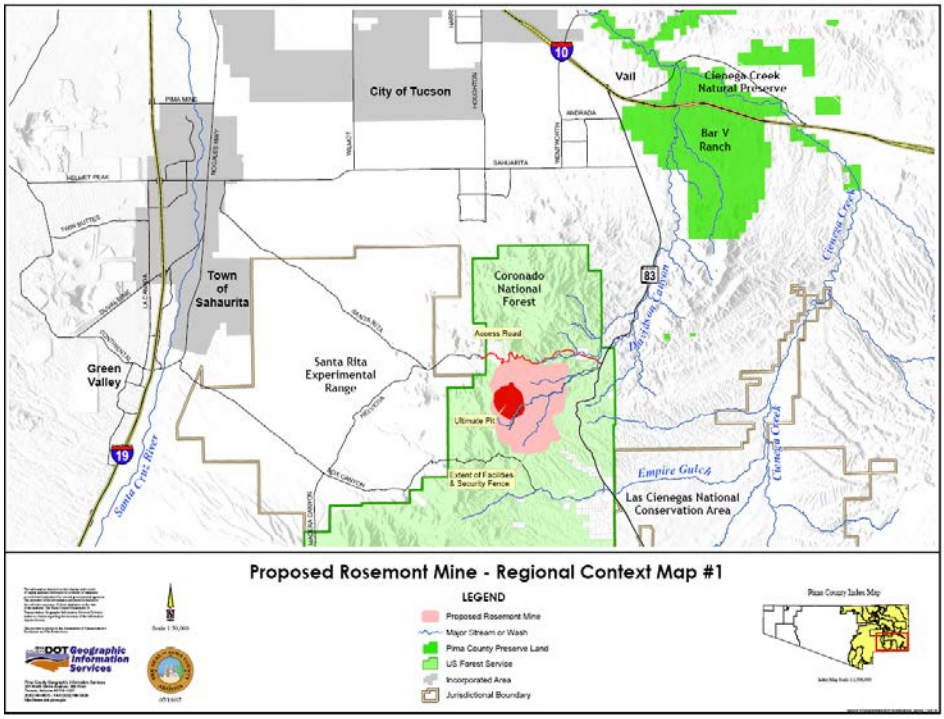


Figure 44. The proposed Rosemont Mine is directly upstream of the Preserve and, if built, will impact surface and groundwater resources of the Preserve.

Figure 45. Surface water from Cienega Creek is currently diverted into this culvert, which takes the water to the del Lago Golf Course. Leaving this water in the stream channel would be beneficial.

This “middle road” can best be described as adaptation, which refers to adjusting management actions in the face of changing conditions. The first line of defense in adaptation is to create *resistance* to change. This often involves efforts at reducing or mitigating impacts on resources that are likely to be impacted in the future. In the case of the Preserve, examples might include purchasing water rights and fencing of additional sensitive areas. Promoting resistance provides a reduction in a threat before it has a chance to test the capacity of a system to withstand change. The next, most widely discussed tenet of adaptation deals with promoting system *resilience* (Turner II et. al. 2003; Tompkins and Adger 2004; Millar et. al. 2007; Heller and Zavaleta 2009). Resilience is the capacity of a system to resist or regenerate from change before that system undergoes a fundament shift to a different state. Just as healthy humans are better able to deal with and recover from disease or illness, so too are healthy ecosystems able to deal with stresses and still return to a “healthy” state.

Fortunately, resilience is built into the dynamic nature of riparian systems such as Cienega Creek. Many riparian plants and systems are adapted to hydrologic and geomorphic disturbances and tolerate both seasonal and annual variation in environmental conditions (Naiman and Decamps 1997). Therefore, resilience strategies should focus on supporting this natural dynamic of riparian systems to return to their natural state following disturbance (Dale et. al. 2001).

Management actions that can foster resilience include reducing anthropogenic threats, reducing fragmentation and increasing connectivity among natural land-cover patches, maintaining adequate representation (e.g., communities and species), protecting key ecosystem features and processes, and focusing restoration efforts to those projects that restore and maintain ecosystem processes and functions (Heller and Zavaleta 2009). Restoration programs that reestablish appropriate hydrological processes, actively intervene with horticultural techniques to propagate and establish native vegetation where necessary, and manage for genetic diversity to facilitate evolutionary processes can build upon the natural resilience of riparian systems. A key action for the Preserve would be to restore diverted flows to Cienega Creek (Figure 45).

The Sonoran Desert Conservation Plan has a number of resilience elements built into a host of actions taken since the plan was enacted including:

- Acquisition of over 71,000 acres of fee-owned (ownership) lands, and over 120,000 acres of leased lands, with particular emphasis on lower elevation communities such as riparian corridors, which had poor representation in the montane-dominated reserve system prior to the initiation of the SDCP;

- Development of a regional reserve design (Maeveen Marie Behan Conservation Land System; see Pima County 2012b) that spans physical gradients such as topography, geology and soils;

- Preservation and repair of connectivity through designation of critical landscape connections and Priority Conservation Areas for specific taxa (see Pima County 2012b);
- Adoption of a new policy to minimize effects of new groundwater pumping on springs and streams;
- Investments in fencing for management of livestock on County-owned lands, and improved pasture management and restoration efforts on County ranches;
- Modifications of stock-watering systems to provide safer and more lasting access to water for wildlife;
- Buffelgrass management in reserves and along County roadways;
- Additional allocation of effluent for riparian projects ("Conservation Effluent Pool");
- Acquisition of groundwater rights;
- Implementation of the Pima County Drought Management Plan.

Continuing and Expanding Monitoring at the Preserve

This reporting summarizes a host of water resource data that has been collected at the Preserve since its inception in 1988. Without these data, we would not know that key resources are on the decline and in need of management and research attention. Going forward, the RFCD plans to continue funding PAG to conduct ongoing monitoring of the Preserve. The County will also commit additional monitoring resources as part of the County's forthcoming MSCP (Pima County 2012b). Known as the Ecological Monitoring Program, the County will conduct more in-depth monitoring of wildlife, vegetation, and other resources at the Preserve on other areas owned and managed by the County (Powell 2010).

This report summarizes data that can inform a conversation about gaining greater efficiencies in the water resource data that is already be collected and more work is need to determine if the monitoring program is sufficient to meeting the management objectives for the Preserve (McGann and Associate Inc. 1994; Pima County Regional Flood Control District 2009) and—if necessary—suggest changes to either the objectives or the monitoring program. For example, it may no longer be prudent to measure flow at the Tilted Beds site (Figure 11) and instead choose a different site to monitor. Such a detailed conversation should happen, but it is beyond the scope of this report to offer specific suggestions. For now, the recommendation is to continue the current monitoring effort, especially considering the declining trends that have been observed.

Future Analyses

This report represents an important first analysis of the water data the Preserve. Additional analysis and modeling can help clarify some of the uncertainties outlined in the discussion. Addition analysis and modeling could include:

1. Determining change in composition, condition, and extent of riparian vegetation since the Preserve was created. This work can lead to estimates of groundwater consumptive use by riparian vegetation.

2. More in-depth analysis of the geomorphologic changes that have occurred since the Preserve was created.

3. Evaluation of extent and timing of both incision and sediment deposition.

4. Isotopic research to determine the relative contribution of summer versus winter precipitation on the shallow groundwater aquifer.

5. Thorough examination of impact of groundwater pumping, with mapping and reporting on locations of non-exempt and exempt (domestic) wells; estimates of consumptive use from these wells; and groundwater modeling to simulate rate and timing of storage and release.

Acknowledgements

This report—and the insights it provides on the condition of the water resources within the Cienega Creek Preserve—would have been possible without the work of many people over the years who had the foresight and persistence to plan and collect the data that make this report meaningful. Many deserve recognition in this regard, but particular thanks go to Julia Fonseca, Claire Zucker, Mead Mier, Rachel Loubeau, David Scalero, and staff at the Arizona Department of Water Resources. Mike List produced Figures 4 and 5 and digitized and produced Appendices A-E. Erik Glenn produced Figure 2. Andy Wigg provide streamflow and precipitation data. Gita Bodner, Jeanmarie Haney, Julia Fonseca, Mead Mier, and Frank Postillion provided valuable reviews of an earlier draft of this report.

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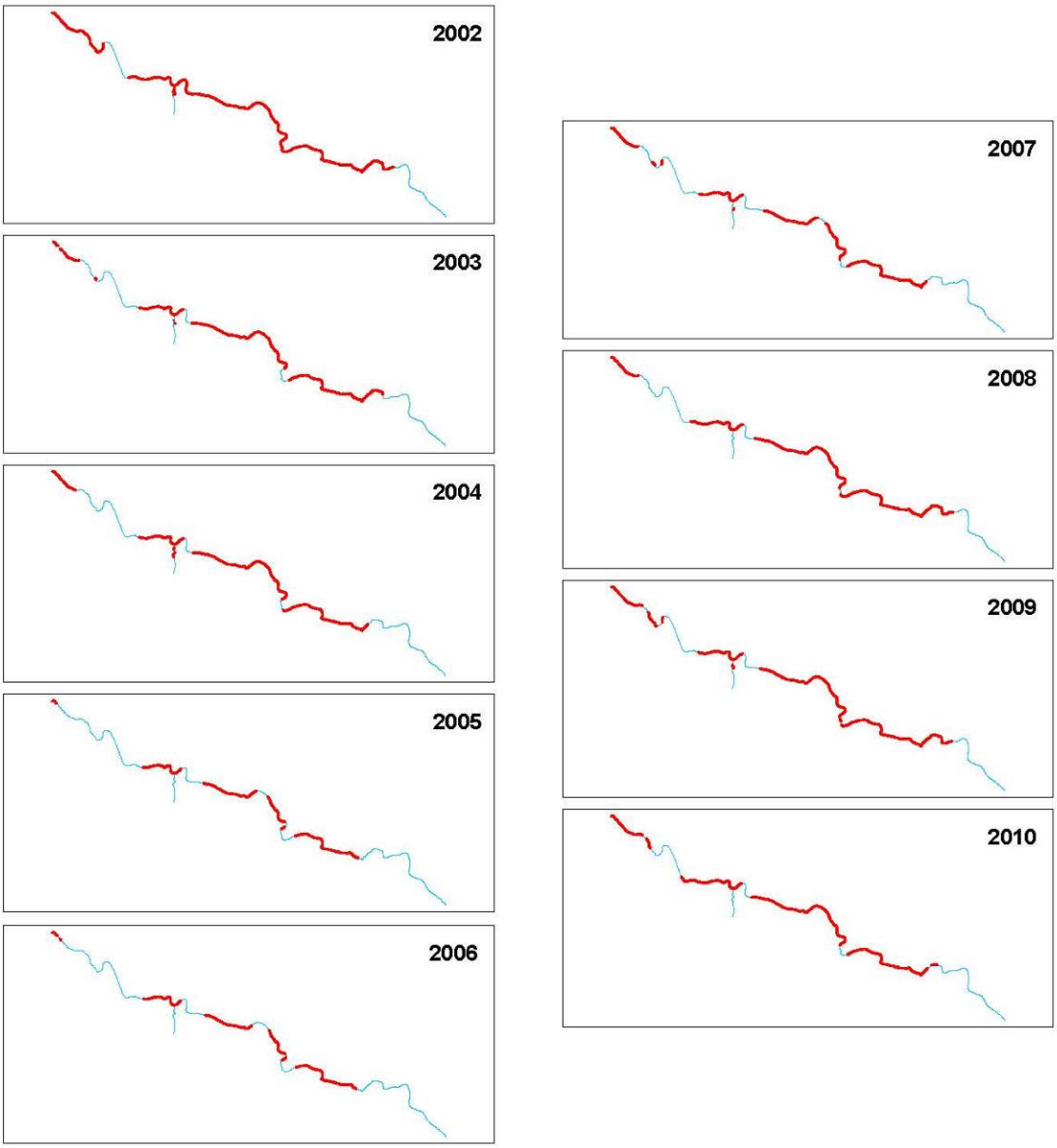
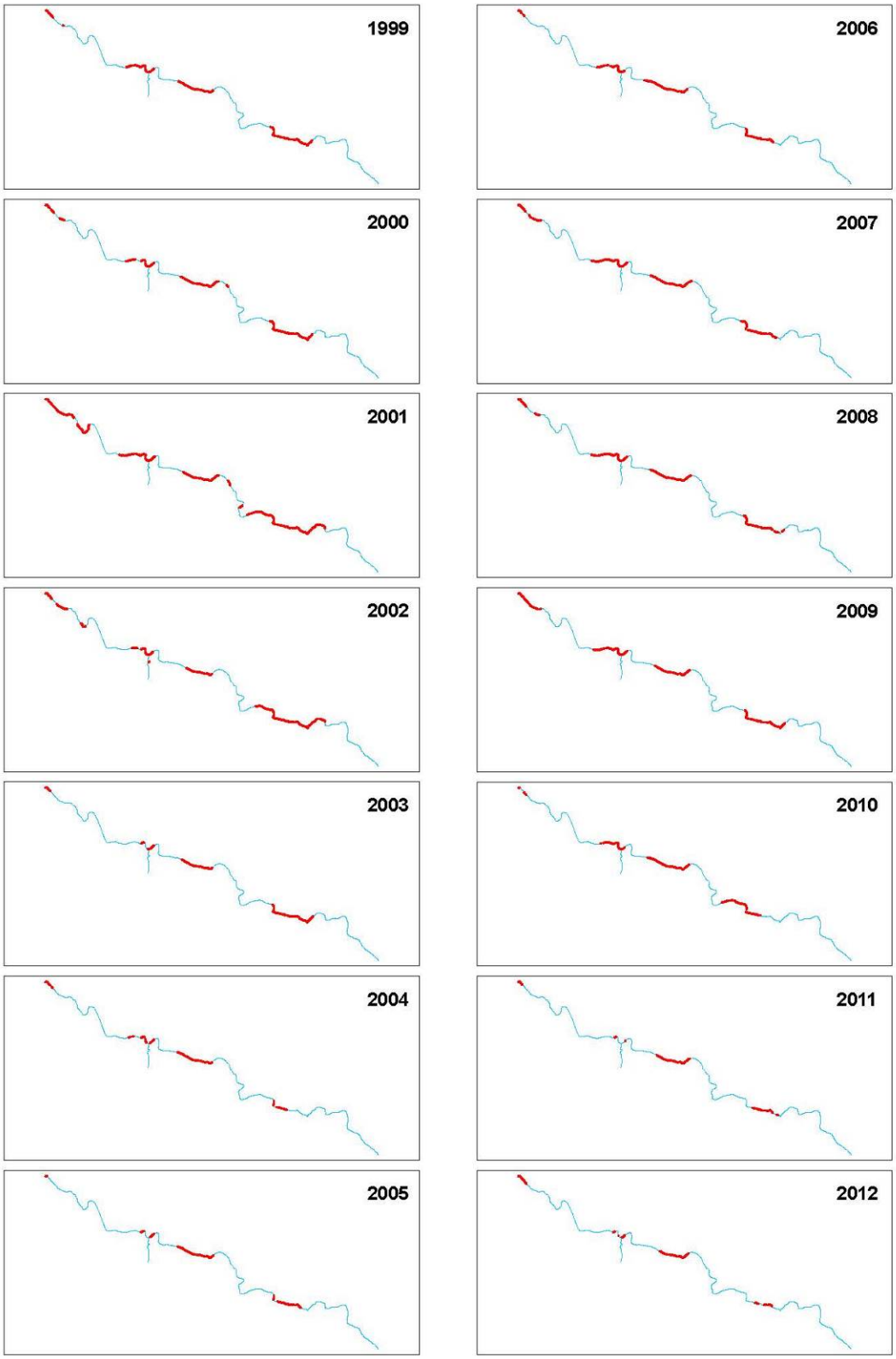
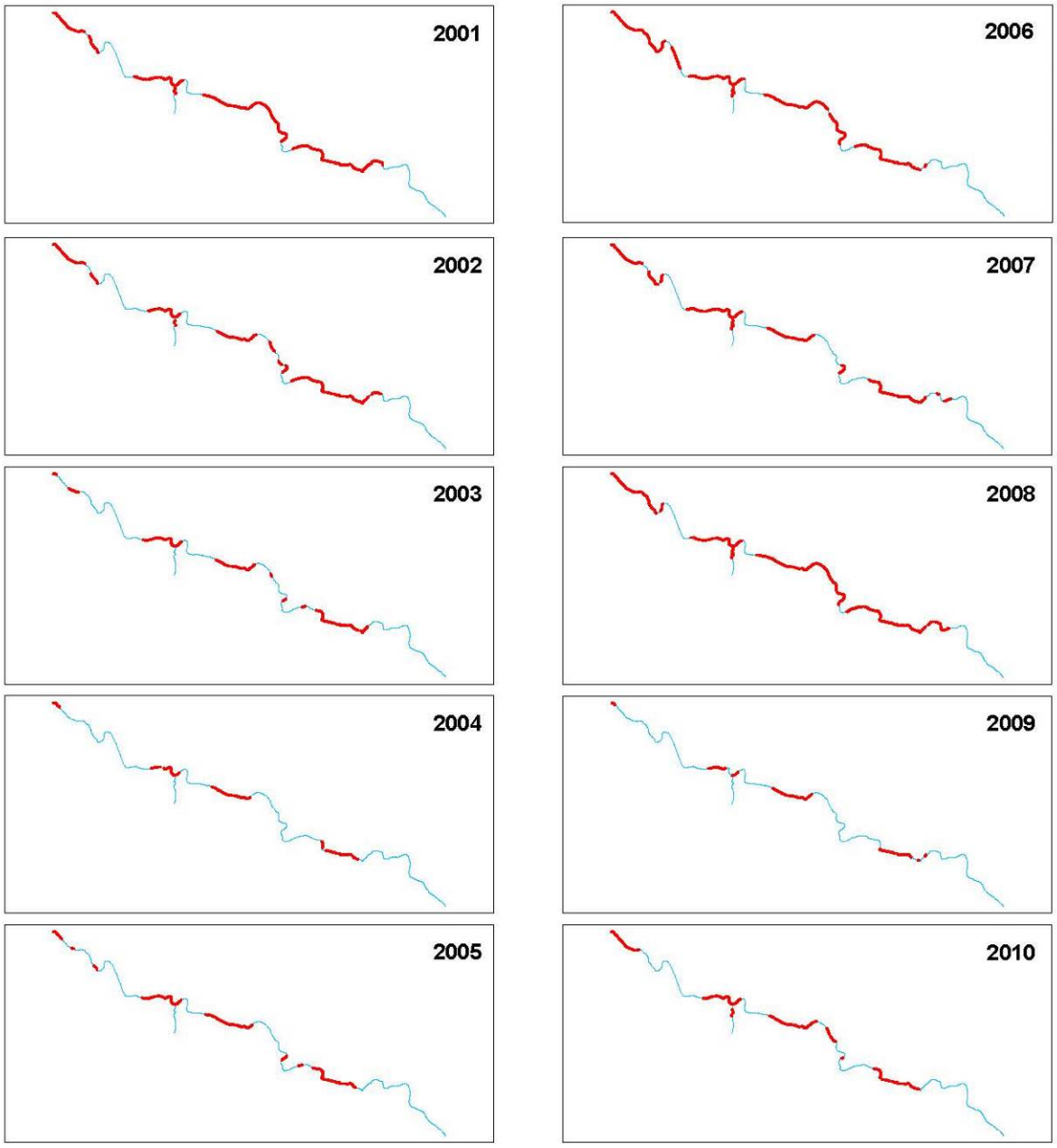


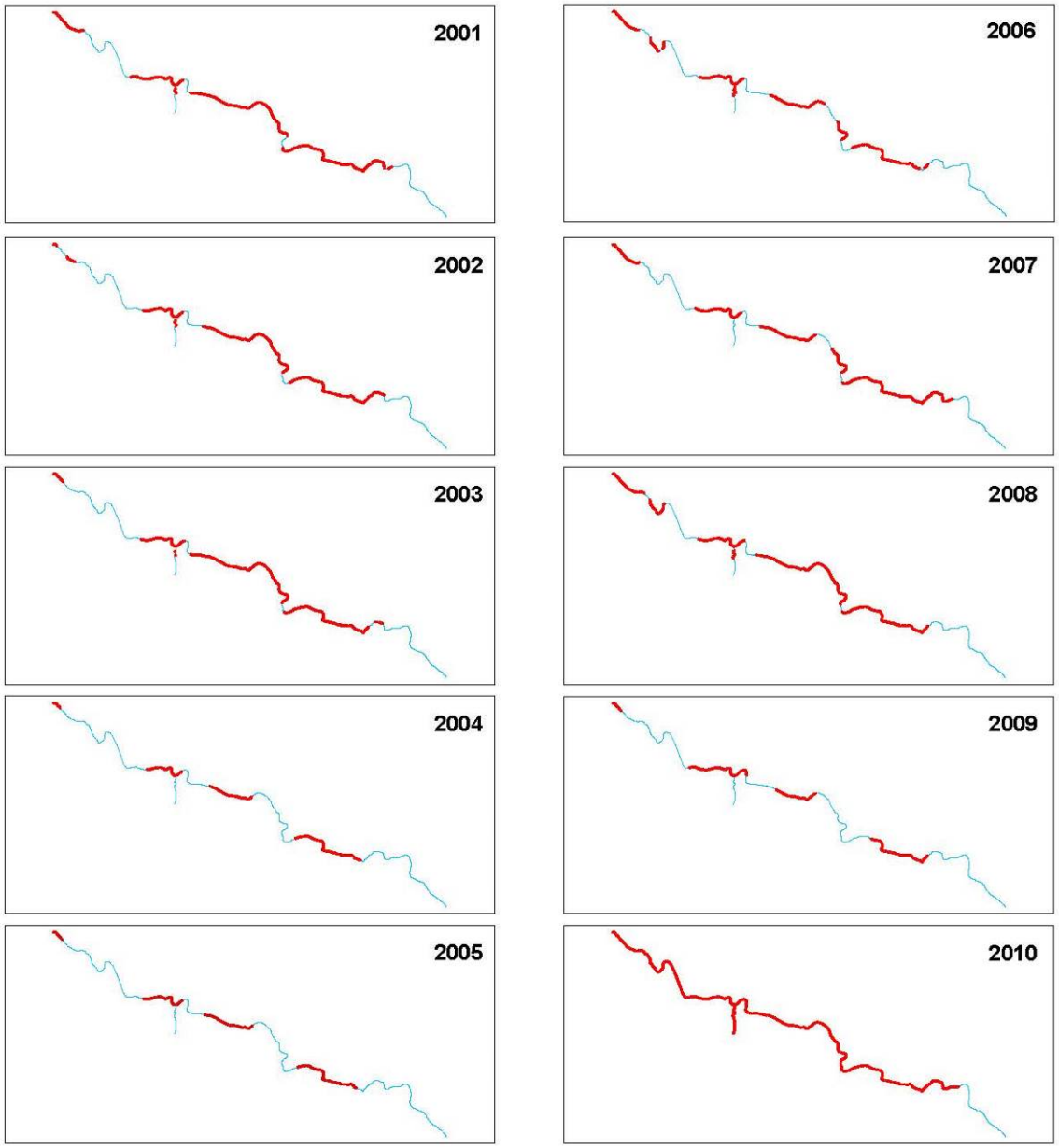
Appendix A. Length of streamflow at the Cienega Creek Preserve, March observations.



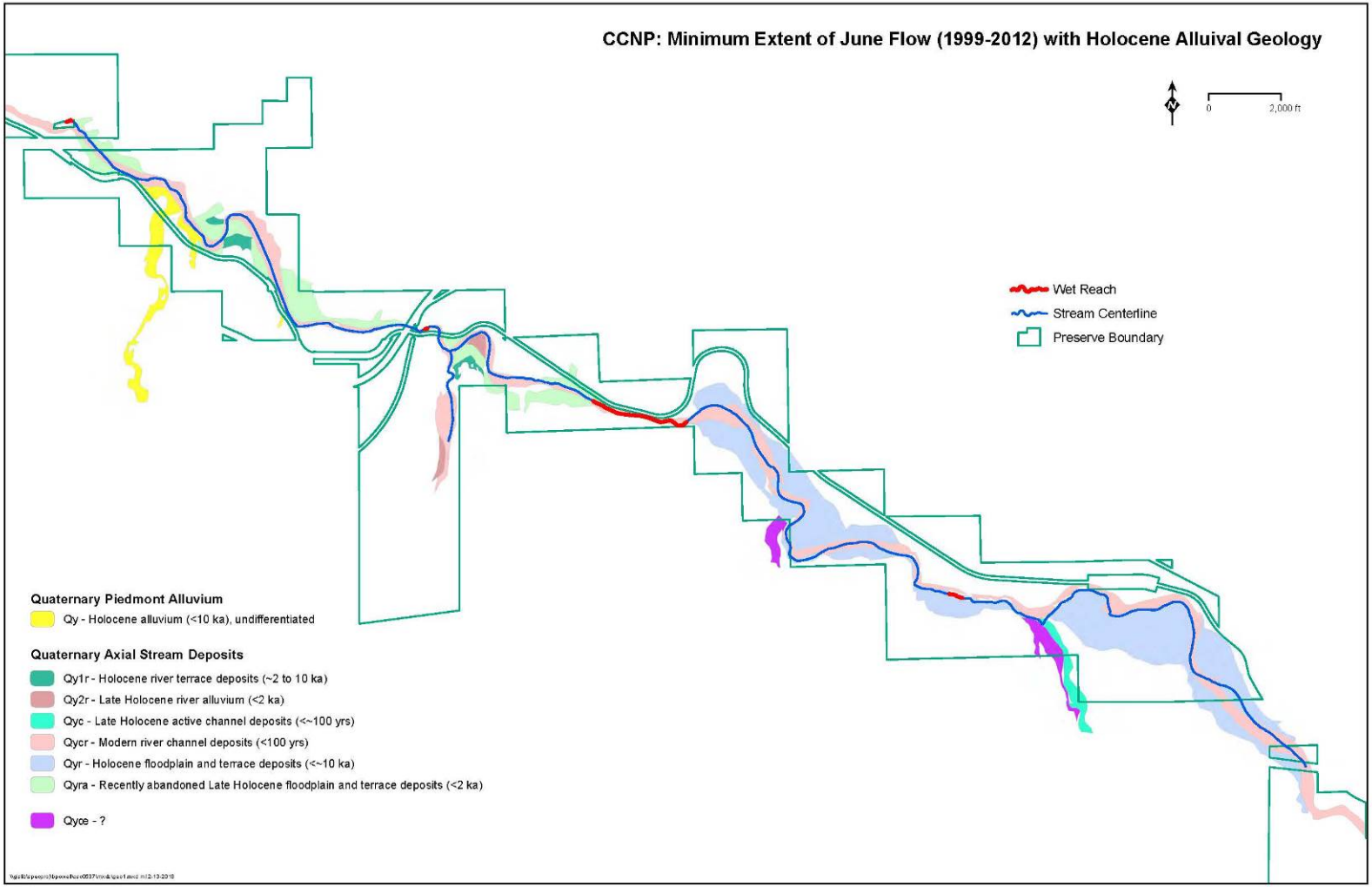
Appendix B. Length of streamflow at the Cienega Creek Preserve, June observations.



Appendix C. Length of streamflow at the Cienega Creek Preserve, September observations.



Appendix D. Length of streamflow at the Cienega Creek Preserve, December observations.



Appendix E. Intersection of June minimum flows with floodplain deposits.