Burro Cienaga Hydrological Monitoring Report, 2007–2014

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Contents

Report summary

New Mexico's Burro Cienaga is one of a sparse number of remaining functional cienagas, or natural wetlands, in the southwestern U.S. Although semi-intact in 2005, its condition was severely degraded. An incised stream corridor cut through the historic wetland at its upstream extent on the Pitchfork Ranch, and watershed conditions generated rapid surface runoff and major flood events. Headcutting and other forms of channel instability were prevalent, making "natural" recuperation of the system highly unlikely. Landowners A.T. and Cinda Cole began work in 2005 to restore the Burro Cienaga watershed, riparian corridor, and historic wetland.

Restoration efforts are aimed at rebuilding this ecosystem's natural resilience to both extended drought and periodic flooding. Improving alluvial groundwater retention is crucial to this process. Shallow groundwater stored in the upper, spring-fed subreach on the Pitchfork releases slowly back into the channel during dry periods, increasing both the spatial and temporal extent of surface flow during dry seasons. Surface water and wetland habitat support a number of rare and endangered species present or successfully re-introduced on the Pitchfork, including the Gila topminnow and Chiricahua leopard frog.

To document and evaluate restoration results, the Coles implemented and funded a variety of monitoring methods. Monitoring incorporates both qualitative methods (annual repeat photography) and quantitative data collection. Hydrologic and geomorphic data are collected at three monumented transects; 3-4 piezometers instrumented with recording pressure transducers were installed on each transect. Each transect and the stream channel profile were surveyed by total station in 2007, the first year of data collection, and again in 2014. Daily precipitation data were collected from two long-term climate stations in or near the Burro Cienaga headwaters in order to evaluate results relative to both seasonal precipitation and to the region's extended drought conditions.

Geomorphic data collected in early 2007 and mid-2014 show that channel instability has been arrested throughout the upstream (historic wetland) reach where the most intensive in-channel work has been concentrated. Vertical complexity created in the channel bed form dissipates flood energy, and substantial deposition has occurred within an 80-m long subreach. Deposition of fine-grained substrate (silt and sandy loams) has aggraded both the channel bed and floodplains within this subreach, supporting dense growths of herbaceous species as well as riparian trees. Hydrologic data demonstrate that alluvial groundwater storage has increased in the subreach, and that continuous seepage from Cienaga Spring, near the upstream Pitchfork boundary, supports the availability of perennial surface water through the upstream reach. A transition zone between perennial and intermittent or ephemeral surface flow occurs at the alluvial fan at the base of Horse Canyon, a major drainage approximately 1 km downstream of the upper Pitchfork boundary.

Restoration work began more recently and is less concentrated below this transition zone. In this subreach, coarse-grained alluvium and intermittent surface flow strongly limit alluvial groundwater storage, both temporally and spatially. Scattered zones of riparian growth exist throughout the downstream reach, but vegetation at the downstream monitoring site is typical; constrained to sparse populations of species adapted to more xeric conditions. Hence, both the geomorphic survey data and groundwater levels recorded from 2007–2014 at this site form a baseline data set for evaluating long-term response to continuing restoration work.

Introduction: Cienagas in the Southwest

Ciénaga is a word commonly believed to translate from the Spanish as "one hundred waters" ("cien agua"). The origin of the word and its variant "ciénaga" is not simple, but the actual root is "silt," or *cieno.* A ciénaga is not a river or creek, but rather an ecosystem dependent on high groundwater levels sustained by surface flows that are typically shallow and slow-moving. Dense, herbaceous wetland species thrive in these environments, capturing and depositing thick layers of fine sediments over time. These southwestern marshes are typically associated with perennial hillside springs and shallow headwater streams, where local geology sustains points of groundwater emission. The geologic features contributing to cienaga formation are often found where faulting processes instigated canyon formation. Historically, cienagas often occupied the full extent of the canyon bottoms in which they were located, extending from one canyon wall to the other.

Their importance is underscored in a number of recent works. For instance, Henderson and Minckley (1984) emphasize the urgency of protecting those that remain:

> Cienegas have been a tremendous resource not only for the endemic peoples, but for the biota as well...Cienegas and other marshland habitats have decreased greatly in...the past century...In light of their continuing disappearance, cultural histories, and importance to aquatic faunas and floras, these dwindling, valuable, as yet little-understood ecosystems...should be given high priority as a unique remnant of our natural heritage.

Stevens and Meretsky (2008) point out the polarity between their oversized ecological importance and threatened status:

> Springs ecosystems are among the most structurally complicated, ecologically and biologically diverse, productive, evolutionary provocative, and threatened ecosystems on earth (and function)...as 'keystone ecosystems,' exerting vastly disproportionate impacts on regional ecology, evolutionary processes, and sociocultural economics in relation to their size.

Common in the Southwest before the 1880's, historic cienagas persist today only as remnants. Needless to say, the presence of water at these sites makes them highly susceptible to alteration for human use. As a consequence, many historic cienagas are incised, eroded, and their historic extent is greatly diminished. Where surface flow remains, it is often confined within a narrow, creek-like feature. Perennial surface flow, which historically sustained the wetland vegetation common to these ecosystems, has been reduced to intermittent or even ephemeral flows. Riparian or xeric vegetation able to survive these conditions replaces the former vegetation community. In former cienagas, willows and cottonwoods are succession species, replacing true cienaga vegetation like sedges (*Carex* spp.), rushes (*Juncus* spp.), grasses, and other marshy flora. Intact cienagas and desert grassland springs are therefore rare habitats, their biota largely eliminated or greatly reduced over broad areas of southern New Mexico. While comprising a tiny portion of New Mexico's total land area, these areas are essential to approximately 80% of all specially classified vertebrate species in New Mexico that depend upon riparian or aquatic habitat at some time during their life cycle (New Mexico Department of Game and Fish 2000).

Burro Cienaga wetland and riparian corridor

Burro Cienaga is one of a sparse number of remaining functional cienagas in the southwestern U.S. The cienaga and the intermittent stream corridor associated with it form a substantial wetland resource, the only natural surface water within a radius of dozens of miles. Its watershed, in far southwestern New Mexico, occupies an area approximately midway between the towns of Lordsburg and Silver City (Map 1), bounded to the northeast by the Continental Divide, and to the northwest by the eastern slopes of the Burro Mountains. Elevations range from 1900 m in the headwaters to about 1500 m at the southern Pitchfork Ranch boundary. The oak– and pinyon–forested canyons of its uppermost watershed segue into the northern edge of the Chihuahuan desert grasslands that are a predominant ecotype of the Pitchfork Ranch (Figure 1). At the southern boundary of the Pitchfork, Burro Cienaga's watershed drains about 45 square miles (Map 2). Fortunately, major threats to other aridland wetlands—namely, groundwater extraction and surface flow diversion—remain absent in this remote corner of New Mexico.

Figure 1. Chihuahuan grasslands on the Pitchfork Ranch.

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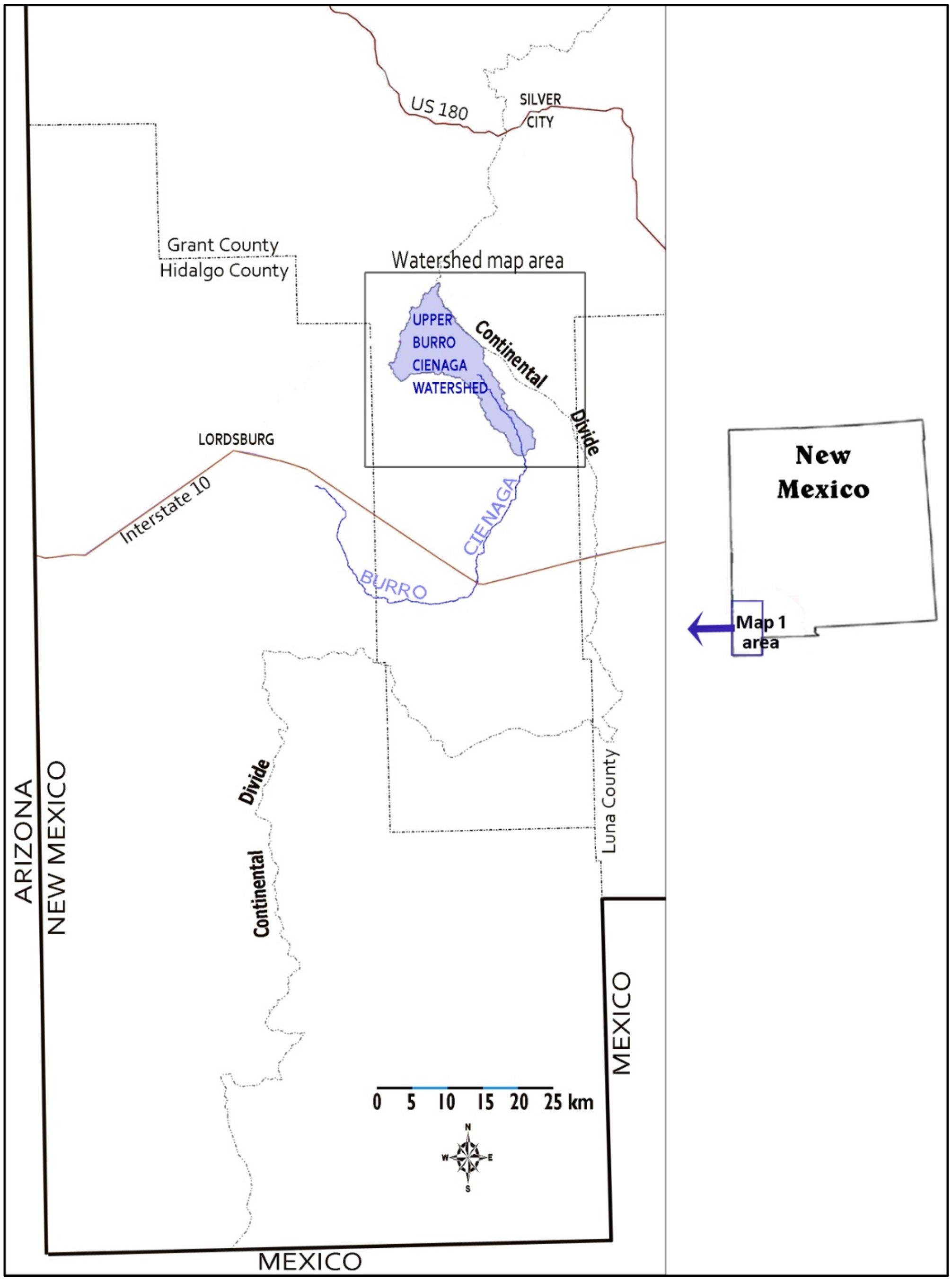
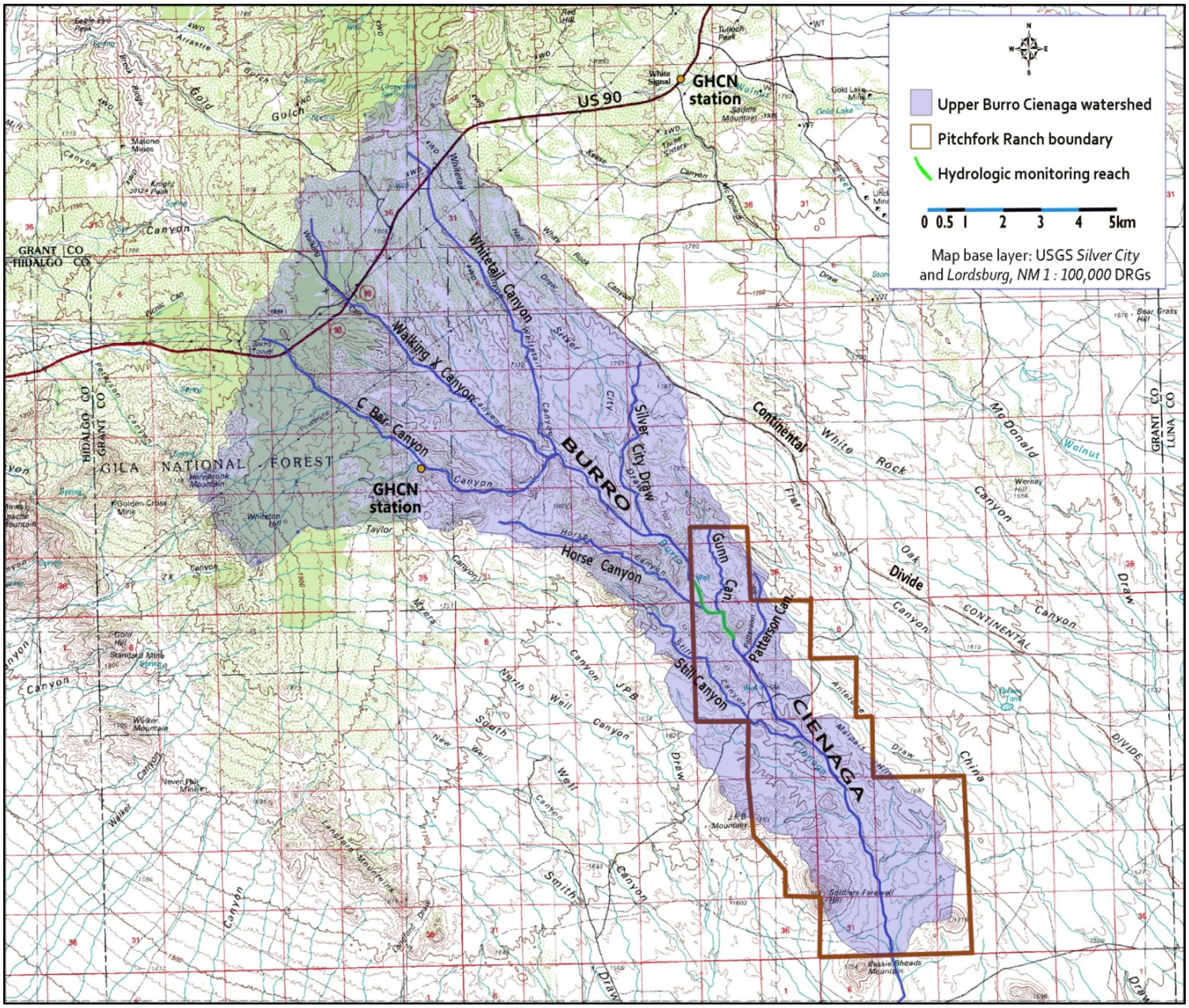


Map 1. Location map for Burro Cienaga and its upper watershed in southwestern New Mexico. The Continental Divide, forming part of the watershed boundary, is shown, along with major roads and towns. The upper Burro Cienaga watershed extends to the southern boundary of the Pitchfork Ranch. Map 2 depicts in greater detail the watershed map area.



Map 2. Upper Burro Cienaga watershed, from headwaters to the southern boundary of the Pitchfork Ranch. The upper watershed drains approximately 45 square miles. Major canyons and drainage features within the watershed are labeled. Daily precipitation data used in this report were collected at the two Global Historic Climate Network (GHCN) stations shown. Green highlighting near the northern boundary of the Pitchfork Ranch identifies the area within the cienaga and its associated stream corridor in which hydrologic monitoring instrumentation was installed in 2007. Flow direction is from north to south.

A perennial spring or seep, Cienaga Spring, emits diffused flow from the left bank of the present-day stream channel near the upstream Pitchfork Ranch boundary (Map 2). Remnant soils and historic evidence show that the historic cienaga (the wetland proper) occupied an extent of 30–50 acres near and downstream of the spring. Surface flow in most of the upstream reach is perennial, transitioning to a sporadically intermittent flow regime farther downstream. Burro Cienaga's stream course continues south approximately 11 miles beyond the Pitchfork boundary, eventually terminating in the closed basin playas just east of Lordsburg

History. Remnants of the Burro Cienaga wetland persisted through a series of typical land management actions and climatic factors between 1840 and 2000—overstocking, draining of wetlands, channelization work, and extended periods of drought—that destroyed the majority of similar ecosystems in the southwestern U.S. during this period. Nonetheless, by 2005 the Burro Cienaga riparian corridor and wetland were in poor condition. Lack of ground cover across the watershed had accelerated surface runoff, and historic channelization work concentrated high flows within the main watercourse, causing deep incision and triggering headcuts throughout its tributary drainages. Major floods were once attenuated by dense wetland vegetation as floodwaters spread across the floodplains, but as channel incision proceeded, high flows were increasingly confined within the deepened channel, reducing alluvial groundwater recharge and contributing to wetland desiccation. As groundwater levels dropped, the historic wetland was reduced to a fraction of its original size. Its sponge-like capacity to store and slowly release water back to the stream channel was nearly lost. Historic floodplains likewise were abandoned as the channel deepened, becoming dry terraces above steep-walled banks.

Restoration goals. Work to restore the Burro Cienaga wetlands and riparian corridor began in 2005 and continues. A fundamental goal of the restoration effort is rebuilding this ecosystem's natural resilience to extended drought and periodic flooding, both a product of the region's climatic variability. Much of the work is therefore aimed at enhancing alluvial groundwater retention in the wetland and riparian zones. As more groundwater is stored in the upper, spring-fed subreach on the Pitchfork, and released slowly back into the channel during dry periods, both the spatial and temporal extent of surface flow should increase during dry seasons.

At the watershed scale, work is aimed at mitigating degradation and slowing overland runoff by increasing herbaceous cover through grazing management (fencing), realigning roads, removing invasive species, and re-vegetation work; rock work mitigates rill and gully erosion in upland features. Work concentrated in the stream corridor and wetland includes berm removal and construction of dozens of grade control structures of various designs, materials and sizes; these include rock-lined pools, baffles, step-down-woven weirs, engineered log jams, liner ponds, and hinge-felled trees (Map 3). Re-vegetation efforts utilize native species such as Coyote willow (*Salix exigua*), Goodding's willow (*Salix gooddingii*) Giant sacaton (*Sporobolus wrightii*), Alkalai muhly (*Muhlenbergia asperifolia),* Vine mesquite (*Panicum obtusum),* and various species of *Carex* and *Juncus.*

Wetland and riparian restoration efforts are designed to enhance conditions resulting in net aggradation of the channel, instream bar features, and floodplains. Once incised, cienagas are unlikely to self restore through natural processes. Channelized flow concentrates the scouring force of floods and increases flow velocity, preventing sediment deposition and water infiltration through streambanks. The restoration approach therefore operates on a feedback-driven process in which 1) slowing surface flows, and re-creating conditions that allow high flows to spread across floodplains and historic wetland, augments alluvial groundwater storage; 2) elevated groundwater levels enhance re-establishment of native herbaceous and riparian vegetation; and 3) dense vegetation effectively traps additional fine sediments, further aggrading the stream channel and banks and dissipating scouring flood energy. Stream banks and floodplains with a substantial component of fine sediments store water longer than coarse gravels and cobble, further enhancing vegetation survival and reproduction.

Wetland and riparian restoration work began in 2005 in the upstream reach of Burro Cienaga on the Pitchfork (Map 3). Additional work has incorporated subreaches of the stream corridor in a downstream direction. Crucially, new structures ("tiers") are built on top of old ones as the streambed and banks aggrade within each subreach in order to enhance continued deposition and aggradation. New techniques have been introduced, like "hinge-felling" selected streamside trees to mimic the effects of flood debris on channel form complexity and deposition.

Species recovery. Burro Cienaga provides habitat for hundreds of plants and animals, including 23 of 37 (62%) of the birds listed as Species of Continental Importance. In addition, populations of a number of threatened and endangered species have been successfully re-introduced on the Pitchfork. These include the Aplomado falcon (*Falco femoralis septentrionalis,)* Gila topminnow (*Poeciliopsis occidentalis occidentalis*), and Chiricahua leopard frog (*Rana chiricahuensis*). The successful reintroduction of the Chiricahua leopard frog is of particular note; these frogs came from a nearby population known to be resistant to the chytrid fungus and their population in Burro Cienaga is increasing. The persistence of surface water and dense vegetation cover are the most important habitat characteristics for this species' success.

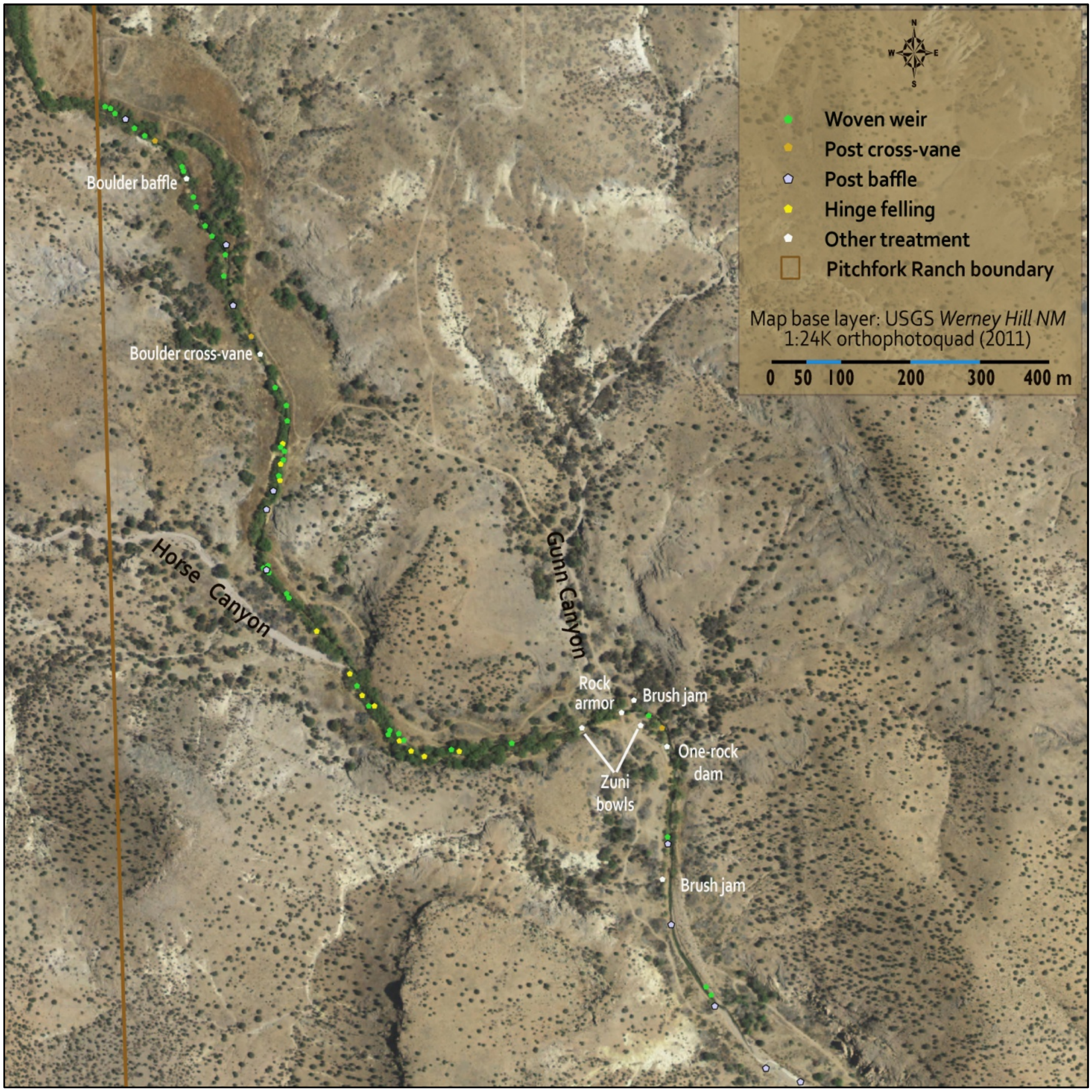
Restoration monitoring summary

An enhanced monitoring regime was implemented beginning in 2007 at Pitchfork Ranch. The monitoring incorporates both qualitative and quantitative methods. The goals are to 1) map restoration structure locations by GPS, 2) document changing ecosystem conditions with annual repeat photos at monumented photo points throughout targeted restoration zones on Burro Cienaga, 3) survey monumented cross-channel transects and the stream profile to document baseline[1] and continuing channel morphology response to restoration treatments, and 4) collect continuous precipitation and groundwater level and temperature data to evaluate long-term alluvial water levels relative to restoration work, and in response to local precipitation.

Funding for all instrumentation and equipment used to collect quantifiable monitoring data was provided by the Pitchfork landowners; installation and follow-up site visits through 2013 were a volunteer effort. This component was therefore necessarily designed to be of relatively limited geographic scope and to minimize return site visits by the technical staff who provided assistance. The greatest cost in establishing the monitoring sites was for instrumentation enabling collection of continuous water data, a substitute for frequent site visits. Over time, the data collected with this instrumentation provide the ability to discriminate between short-term climatic effects on alluvial groundwater levels, and more profound improvements in alluvial storage resulting from channel and floodplain aggradation and the capture of fine, water-retaining sediments.

Qualitative monitoring: GPS mapping and repeat photography. Each restoration structure is mapped by hand-held GPS and details of each structure's design, approximate extent, and any modifications are documented. Between September and October each year, repeat photos are taken at 10 sites within the area shown on Maps 3 and 4. Each photo site is marked with a numbered "monument"—typically, a natural feature, installed post, or rock cairn. At a minimum, photos show the stream corridor in both the upstream and downstream direction.

[1] "Baseline" condition in this case was 2 years after installation of the initial series of restoration structures in the upstream reach of Burro Cienaga on the Pitchfork Ranch.



Map 3. The Burro Cienaga monitoring reach included in this report, from the upstream end at the Pitchfork Ranch boundary past the Gunn Canyon confluence, showing the location and description of each restoration structure completed and mapped in this reach, 2005–2012. Willow-woven weirs, and vanes or baffles constructed of locally-harvested juniper posts are most commonly used, although inexpensive "hinge-felling" of near-channel trees has been more commonly used as vegetation density increases since restoration work began. Rock or boulder work is utilized where needed for stability in areas of high-velocity flow or steep drops in the channel bed.

Map 4. Hydrologic monitoring instrumentation, surveyed transects, and photo point locations in the Burro Cienaga monitoring reach included in this report, from the upstream end at the Pitchfork Ranch boundary past the Gunn Canyon confluence. Repeat photographs documenting changing conditions are taken annually from each photo point. Restoration work began in 2005 in the subreach upstream of Gunn Canyon, and the most extensive repeat photography is concentrated in that subreach. Additional repeat photo points have been established as restoration work proceeds downstream.

Quantitative monitoring: Geomorphology. Five permanent survey controls (5/8" black iron stakes, driven ~ 0.5 m below ground surface) were placed in the monitoring reach (Map 4) in 2007. Each was marked with a labeled white PVC sleeve. The survey controls ensure accurate repeatability of future surveys. Three cross-channel transects were then established; in upstream to downstream order, these are identified as P1, P2, and P3 (Map 4). Each transect is situated perpendicular to streamflow in the active channel, and extends well up onto the adjacent terrace surface on either side of the channel. Transect mapping was completed with a Topcon total station (GTS-226) and Recon data logger, utilizing standard plane survey methods. Elevations were mapped at all substantial slope breaks along the transect. A segment of the upstream stream profile along the channel thalweg, from the Pitchfork Ranch boundary to the P2 line, was also mapped in 2007.

The survey data were initially stored as a series of x, y, & z coordinates relative to an arbitrary datum and origin assigned to one of the survey controls. Internal survey precision is +/- 0.02 m, horizontal and vertical. Arbitrary grid and elevation coordinates were then transformed to real-world coordinates (UTM NAD83, m), using waypoint-averaged coordinates (accuracy: +/- 3 m) collected by a Trimble GeoExplorer II GPS unit at three of the survey controls. Coordinate transformation utilized Terramodel (v. 10.4, Trimble Corporation) software to shift and rotate the data set in order to retain internal survey precision. The resulting finalized coordinate and elevation sets were also transformed into standard transect stationing and elevation format.

In early 2014, a repeat survey of the three transects and the stream channel profile was completed. The data were transformed to standard stationing/elevation format as described above, and overlaid on graphs of the 2007 survey data for evaluation.

Quantitative monitoring: Groundwater and precipitation. To collect continuous water level data, at least three steel piezometers were installed on each of the transects in 2007 (Map 4), and surveyed to a common datum with the transect. Two piezometers were installed on the left bank (all "left" and "right" in this report are as viewed facing downstream) and at least one on the right bank. Piezometer locations are listed in Appendix 1. Project constraints precluded installation of a surface stage gage in the channel, but we hope to add this component within the next year. The piezometers are constructed of galvanized drive points with a 0.6 or 0.9-m 60-gauge stainless steel screened interval, coupled to lengths of solid galvanized pipe and manually driven below ground surface to depths ranging from about 3 to 4 m. Steel piezometers were used for durability and relative ease of installation by volunteers.

One drawback to using piezometers in this situation is the potential for fine substrate to clog the screened interval over time. This presented no difficulty at transect P3, where the substrate is composed of sand and gravels. However, in the upstream subreach (through transects P1 and P2), the near-channel floodplains are more typically composed of substrate ranging from sandy loam to silt/clay. The silt component at the contemporary terrace level is much greater than at floodplain level, and a subsurface clay component reflects the effects of the historic wetland on soil conditions. In some ways, observation wells constructed of PVC, with a longer screened interval, would be the appropriate equipment under these conditions. However, the likelihood of their destruction by the extreme, high-velocity flows that occur with some frequency in Burro Cienaga was near-certain. To keep the screens as clear as possible, we used an inertial hand pump (Solinst Corp.) during site visits. This equipment is designed to forcibly draw groundwater through the screen, a "purging" action that effectively clears all fine particles from the screened interval.

Three piezometers on each transect were instrumented with a recording pressure transducer (Solinst Corporation) set to record water levels at hourly intervals. Manual measurements of water depth validate the recorded water levels during periodic site visits to download the instrumentation. The effects of barometric pressure on groundwater level are adjusted in Levellogger software (v. 4.2, Solinst 2012), using simultaneous barometric data recorded by a Barologger (Solinst Corp.) also installed at the site. Each piezometer measuring point (MP) was surveyed to a common datum with the other mapping data collected on the transect, allowing all water level data to be transformed to water level elevations, and analyzed relative to the stream channel and ground surface.

Local precipitation data were collected by recording tipping bucket (Onset Corp.) near the upstream end of the project reach (ca. P1), and daily precipitation data were obtained from two Global Historic Climate Network (GHCN) stations of the National Climatic Data Center in or near the Burro Cienaga headwaters (Map 2; data available at https://gis.ncdc.noaa.gov/). Daily precipitation data for 2007–2008 were available from station USC00299691, "White Signal," at an elevation of 1824 m and about 4 km east of the Continental Divide. Daily precipitation records are available since November 2008 from Station US1NMGR0026, "Silver City 24.1 SSW," about 4 km east of Hwy. 90 in the Burro Cienaga headwaters at an elevation of 1907 m. Data from these two stations are used in this report.

Results

Repeat photos. Pages 14 through 22 present repeat photos from the 10 photo points shown on Map 4. Photo point coordinates are listed in Appendix 2.

The repeat photography documents changing conditions throughout the Burro Cienaga corridor, particularly in the reach through the historic wetland, where the greatest amount of active restoration work has occurred. In general, they depict localized channel and bank aggradation accompanied by an increasing density and cover of herbaceous plants, including obligate wetland species. Pool features that were identified in 2005 for long-term monitoring appear longitudinally stable, although some pools sporadically fill and are scoured of sediment depending on flood magnitude, rate of recession, and seasonality. During some years, the photos were taken shortly after high-magnitude floods, documenting resilient riparian and wetland habitat resistant to scour or major lateral erosion.

Photo point 1, view downstream.

Clockwise from upper left: 2005. Channelized corridor of Burro Cienaga at the upstream Pitchfork Ranch boundary. Diffused groundwater seepage through the left channel bank in this subreach sustained near-channel herbaceous and woody riparian vegetation, but obligate wetland species were absent. The channel was incised approximately 2 m below the historic wetland elevation. **2007.** Slight aggradation. **2010.** Increasing density of herbaceous wetland vegetation on floodplain, continued channel aggradation, and some obligate wetland plants colonizing areas at water's edge. **2013.** A series of woven weirs in this subreach are built up as the channel bottom aggrades; the three most recently constructed "tiers" are visible but nearly buried by additional aggradation. A scour pool (not visible) formed just downstream of the flood debris at left center, at the P1 transect.

Photo point 12, view upstream.

Clockwise from upper left: 2006. A recently installed post baffle is visible on channel right (left edge of image). Sedge has colonized the channel bottom but the channel's steepness appears to increase the stream's velocity enough, even at low flows, to flatten this vegetation. **2008.** Deposition has partly buried the post baffle. **2010**. A variety of herbaceous and riparian species have colonized the low banks and cover on the higher adjacent terrace has increased. **2013.** Sedge and rush species still inhabit the area of surface flow, but dense ground cover vegetation is well-established across the floodplain and adjacent terrace.

Photo point 2, view downstream.

Clockwise from upper left: 2005. A long deep pool formed at this location, but bankside vegetation recruitment was nonexistent; the few trees were decades old and the large juniper on the left bank suggests relatively dry conditions even within 2 m of the incised channel. **2007.** Some obligate wetland vegetation is beginning to establish at the site. Rock stabilization work at the upstream end of the pool enhanced deposition and was colonized by wetland plants, headcutting ceased. **2010**. Additional recruitment and growth of riparian and wetland vegetation. **2013.** Filling or re-scouring within the pool occurs during some floods, but its position remains stable despite evidence of very high-magnitude flooding at the site. Wetland and herbaceous vegetation is well-established.

Photo point 2, view upstream.

Clockwise from upper left: 2005. Upstream end of the pool shown in previous photos; sparse herbaceous vegetation occupies the low right bank. **2009.** Stabilizing rock work at upper end of pool; herbaceous wetland species beginning to occupy floodplain. **2012.** Vegetation stabilizes and enhances deposition. **2013.** The right bank is densely vegetated with diverse vegetation, including herbaceous wetland species; vegetation density on the higher-elevation left bank has also increased.

Photo point 4, view upstream.

Clockwise from upper left: 2005. Surface flow is present, and this view clearly shows the extent of channel incision below the elevation of the historic floodplain/wetland on the right half of the image. A side cut, visible just beyond the hat, has eroded through the left bank. Herbaceous vegetation is sparse, with many annual nonnative species present. **2007.** Streamside woody riparian vegetation is denser and taller; native herbaceous vegetation has expanded slightly upward toward the terrace level. **2009.** Increased ground cover in side headcut and riparian expansion. **2013.** Previously sparse stands of obligate wetland species on the left channel bank are denser and more extensive, and native grass cover on the left terrace has increased. Erosion in the left bank headcut has been arrested.

Photo point 5, view downstream.

Clockwise from upper left: 2005. The barren remnant of an historic road on the left floodplain is visible, left center of image. Restoration included closure of this road segment. **2008.** Some native grass and forb cover has re-occupied the old road surface. **2010.** Growth and expansion of woody riparian species cover. **2013.** Continued increase in native grass cover.






Photo point 6, view downstream (left) and upstream (right).

Top to bottom: Transition subreach between the historic Burro Cienaga (wetland), and the riparian zone characterized by intermittent flow downstream of Horse Canyon. Geologic controls constrain this subreach, through the alluvial fan at the base of Horse Canyon, and probably precluded farming the adjacent terraces. **2005.** Native grasses were the predominant ground cover. **2006.** Surface flows overtop the relatively low floodplain and terrace, and no substantial geomorphic channel change occurs during even high-magnitude floods. **2009.** Obligate wetland species (particularly sedge and cattail) are densely established through this subreach.

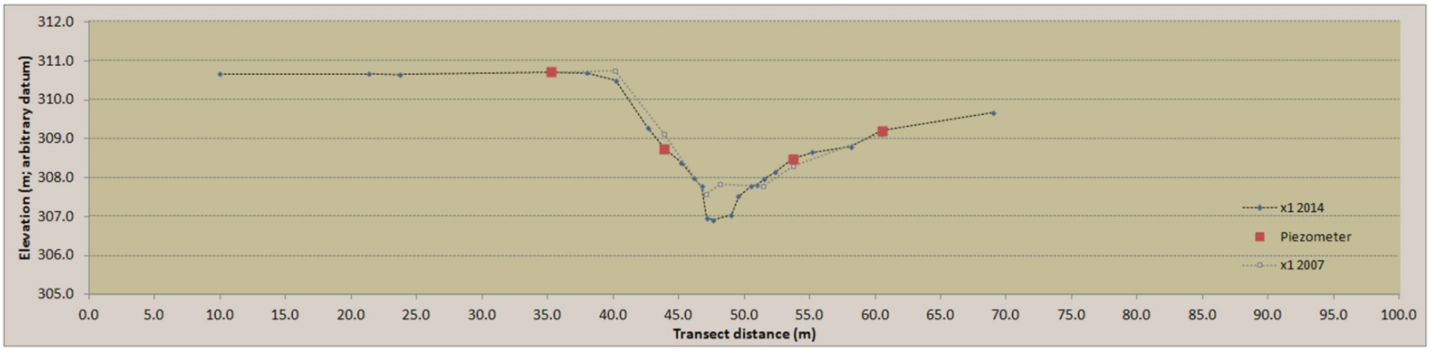
Photo point 7, view downstream (left) and upstream (right).

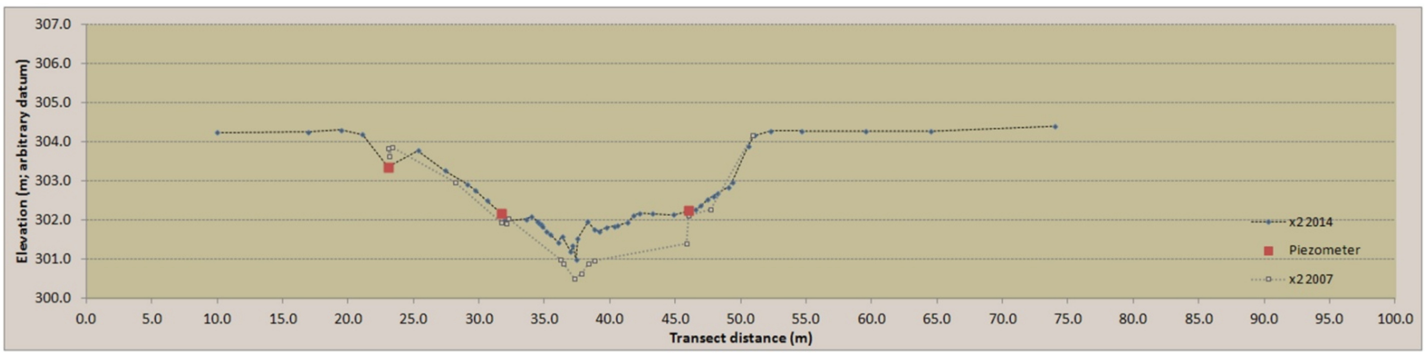
Top to bottom: The downstream end of the transition subreach below Horse Canyon. **2009.** Natural bedrock control bypassed by the stream channel; lateral movement exposed the roots of the willow on channel right and eroded the right terrace (left side of upstream view). **2012.** The channel wanders through coarse sand and gravel newly deposited in this reach (note that the upstream view is from nearer the channel than in 2009). **2013.** Aggradation continues.

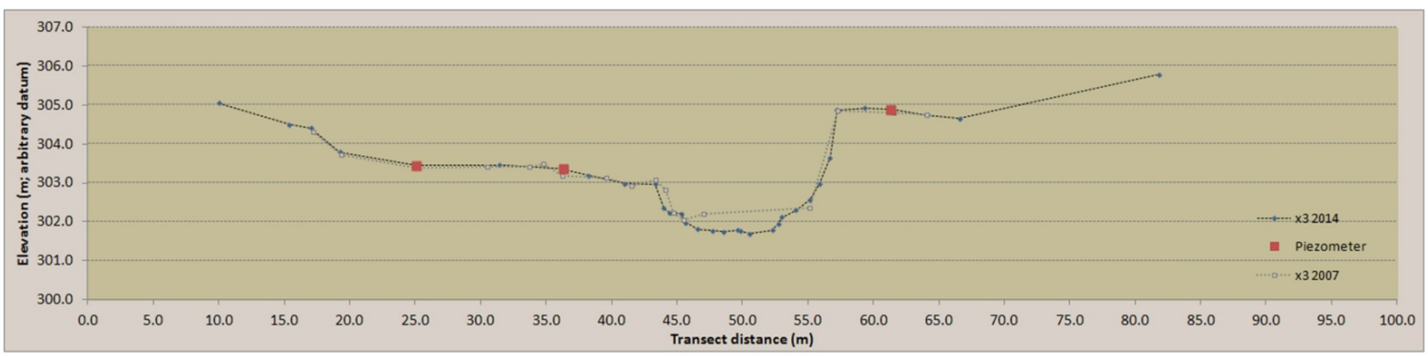
Photo point 16, view downstream (left) and upstream (right).

Both images from 2012. Intermittent streamflow characterizes the Burro Cienaga stream corridor downstream of the bedrock controls on the channel's course between Horse and Gunn Canyons. The channel and floodplain substrate, composed largely of coarse sand and gravel, is non-cohesive and drains rapidly after surface flow events. Vegetation is sparser and more xeric species inhabit the floodplains than in the upstream subreach, although pockets of riparian and wetland habitat occur sporadically throughout the remainder of Burro Cienaga's course through the Pitchfork Ranch.

Geomorphologic survey data: ***P1-P3 transects.*** Initial (baseline) surveys of each channel transect were conducted in 2007, two years after restoration work began. Mapping data from the cross-channel transects in 2007 and 2014 document differing results at each site. Figures 2a-2c show the survey results.







Figures 2a–2c (top to bottom). Transect lines P1 (x1), P2 (x2), and P3 (x3) as surveyed in 2007 and 2014. Elevations are based on arbitrary survey datums established for the work: a single datum for the P1-P2 subreach, and a second for the P3 subreach surveys. The vertical and horizontal scales are the same on all graphs. Red squares mark the location at ground surface of each piezometer installed on the transect line; "a" piezometers are farthest left and "c" (P2 and P3) or "d" (P1) piezometers farthest right.

Transects P1 and P2 are in the now perennial historic cienaga reach (Map 4), where streamside vegetation was generally well-established by 2007 if not earlier (e.g., see photo points 1, 2, 4). Transect P3 was established in the intermittent stream reach downstream of Gunn Canyon. Channel and bank substrate in the subreach upstream of the Horse Canyon confluence is more cohesive and fine-grained than that farther downstream, including in the P3 subreach (Figures 3 and 4). Restoration structure installation and other efforts 2005–2014 were substantially more concentrated in the upstream subreach than in the P3 reach (Map 3).

The surveys document the typical differences in channel form between the perennial upstream subreach and the intermittent reaches farther downstream. On transects P1 and P2, with perennial surface flow, a narrow "inset" channel occupies the larger channel form. The larger channel (on P1, for instance, between transect distances 40–65 m; on P2, between distances 25–50 m) contains flow during all but the most extreme flood events. Low flows are contained within the inset channel, which is stabilized by dense streambank vegetation sustained by perennial surface or near-surface water.

The root systems of dense streamside vegetation are highly resistant to erosion, and its above-ground biomass effectively disperses flood energy. Scouring floods may incise the inset channel, but are less likely to result in major erosive change across the larger channel form. Conversely, along intermittent stream reaches, floodplain vegetation is typically composed of xeric upland shrub and bunch grasses scattered sparsely across the floodplain. Floods through such areas are more likely to result in more extensive channel change. Lateral scour or erosion across the full width of the channel bed is possible; conversely, localized deposition of massive quantities of sand, gravel, or coarser substrate may occur. Deposition and lateral stability are more likely where conditions support the establishment and survival of denser vegetation cover.

At both P1 and P3, a net decrease in the elevation of the channel bottom occurred between the 2007 and 2014 surveys, but the form of incision differed between the two transects. At P1, the thalweg within the low-flow channel scoured about 0.7 m, creating a pool feature on the transect, but there was little change in the larger flood channel form. The channel bottom at P3 was eroded, on average, about 0.5 m, across a width of nearly 10 m, and lateral erosion widened the channel slightly. The right floodplain on the P1 line aggraded about 8 cm between the two surveys. However, although the left floodplain at P3 is low and therefore relatively easily overtopped during floods, there was no net deposition on the floodplain between the 2007 and 2014 surveys.

Figures 3a (left) and 3b: Permanent monitoring transects P1 and P2, March 2014. The person in each image is standing on the transect line.
3a: View left to right across transect P1. Dense herbaceous vegetation occupies the channel banks and both of the large, dormant *Salix* visible are decades old. The pool on the transect was approximately 1 m deep on the survey date. 3b: View left to right across transect P2. Riparian trees (*Populus, Salix*) at this transect appear younger than those on P1. Herbaceous bank cover is extremely dense. Maximum water depth on the transect during the survey was approximately 0.8 m.

The net result of surface flows through the P2 transect between 2007 and 2014 was very different than at P1 or P3. A substantial volume of material was deposited between surveys, aggrading both the channel and the adjacent floodplains. The thalweg elevation increased about 0.5 m, and the right floodplain aggraded nearly 1 m from 2007–2014.

Figure 4. Sparse floodplain vegetation on transect P3, viewed from right to left. The person at center is standing at the left end of the transect. Shallow surface flow was present in the channel (bottom of image). May 2014.

P1-P2 profile. To evaluate the changes at transects P1 and P2 relative to the larger stream corridor, the profile survey data from 2007 and 2014 were overlaid for comparison. Figure 5a shows the graph created from the stream profile surveys in the P1-P2 reach.

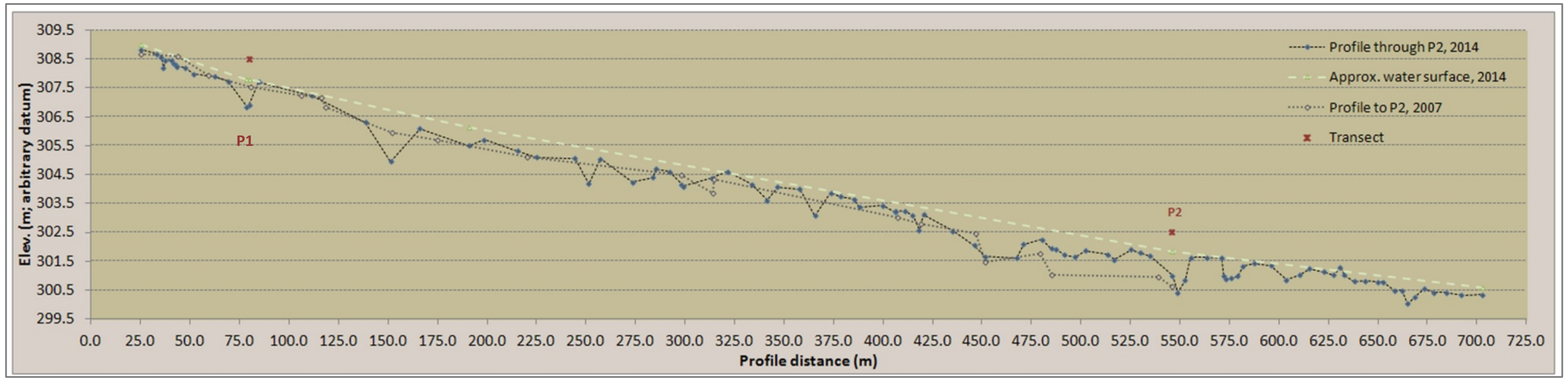
The most obvious result shown in Figure 5a is an increase in the complexity of the channel profile from 2007 to 2014. During the profile surveys, points are mapped at all major slope breaks. Where restoration structures like weirs are still visible above the channel bed (i.e., local bed aggradation is not yet sufficient to bury the structure), they are also mapped. In 2007, the channel bed slope through the approximately 550 m distance from the upstream Pitchfork boundary to transect P2 was relatively uniform; that is, there were few pools, true riffles, or mid-channel bars present. Parts of some of the weirs constructed during the earliest restoration efforts were still visible and were mapped; for instance, just downstream of transect P1 (at profile distance 110 m), and about midway between transects (at profile distance 310 m). Two steep drops upstream of transect P2 appeared to be likely zones of incipient headcutting, absent additional work to mitigate those effects. The overall slope through the 550-m reach was 1.54%.

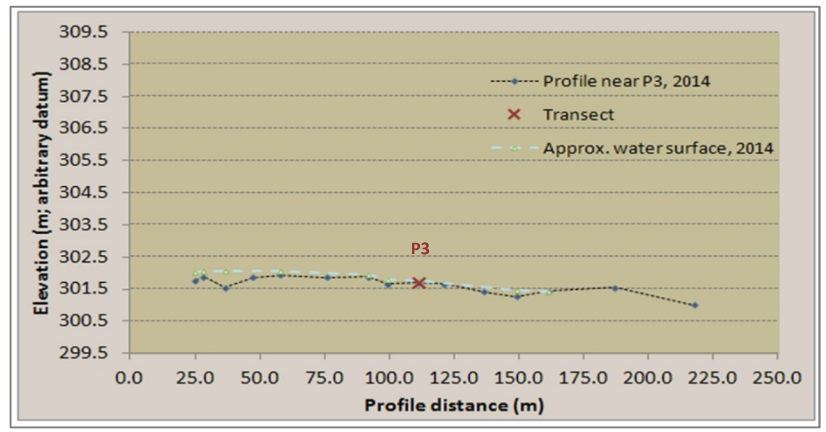
In 2014 the stream profile was more complex, including three large pools and a number of smaller pools formed between riffles (or weirs) and mid-channel bars. Few of the 15 weirs constructed between the upstream boundary fence and the P2 transect (Maps 3 and 4) remained visible above the channel bed or water surface on the survey date, the structures were either buried by aggradation or submerged. Five weirs were mapped during the survey. Dense bank and near-channel vegetation indicated that the increasingly complex channel profile was relatively stable. Between 2007 and 2014, one large pool formed at the P1 transect and another approximately 75 m downstream of it. A third large pool (approximate profile distance 440–465 m; also see views from photo point 2) persists within the formerly unstable subreach above transect P2. Substantial aggradation occurred throughout the downstream end of this subreach (profile distance 470–550 m), raising the channel bed an average of 0.3 m.

Overall channel slope within the same 550 m subreach (upstream boundary to transect P2) decreased slightly, to 1.43%. Downstream of P2, the slope of the channel bed flattens substantially. In this subreach (profile distance 560 m to the downstream end of the 2014 survey), the bed slope is about 0.8%. This mapped subreach occupies the upstream end of the transition between perennial and intermittent flow above Horse Canyon and the alluvial fan deposited at the canyon's confluence with Burro Cienaga (see photo points 6 and 7 in the section on Repeat Photography above).

P3 profile. Figure 5b shows the graph of the 2014 profile survey in the P3 reach; the channel thalweg in this reach was not surveyed in 2007, so no comparative data are available. To date, fewer restoration structures have been placed in the intermittent P3 subreach than in the P1–P2 subreach. A post baffle extends into the channel from the right bank immediately upstream of the P3 transect, and two sets of woven weirs were installed approximately 100 m downstream of the transect (Maps 3 and 4).

The channel bed and much of the floodplain in the P3 subreach are composed of non-cohesive sands and gravels, likely to become highly mobile during major floods, and both the channel profile and its cross-section morphology may frequently be re-configured by such events. On the survey date, the thalweg profile form was relatively uniform (Figure 5b). The slope of the channel bed was much flatter than in the upstream subreach, about 0.5%. The only major pool form in the surveyed subreach was near the upstream end of the reach; the pool was 19 m long with a maximum water depth of nearly 0.5 m on the survey date. Obligate aquatic and wetland vegetation species were present, including watercress, cattails, and sedge species (Figure 6), indicating that perennial surface or near-surface water probably now persists at and near this pool.





Figures 5a (top) and 5b (bottom). Figure 5a: the Burro Cienaga thalweg profile as surveyed in 2007 and 2014 in the subreach from the upstream Pitchfork boundary line through transect P2. Surface flow, including pools nearly 2 m deep, was present throughout the reach during the 2014 survey. The position where each transect crosses the channel profile is labeled.
5b: the thalweg profile mapped through the P3 transect line in 2014. Shallow surface flow was present through most of this subreach in 2014. The position of the P3 transect on the profile is labeled.

Figure 6. View toward pool at upstream end of P3 profile from the left terrace on the P3 transect; cattails and other obligate wetland species are well-established on the pool's margins. The juniper post visible in the foreground, bottom center of image, forms part of the post baffle immediately upstream of the P3 transect (Maps 3 and 4).

Precipitation. The extreme climatic variability of the southwestern U.S, both seasonal and inter-annual, can obscure cause-and-effect in "snapshot" evaluations of restoration work results. For instance, riparian habitat condition may appear very different in July of a year with above-average spring rainfall than in July of a very dry year. Long-term monitoring helps to address this difficulty by providing the means to evaluate trends over time. Examining differences over time in the hydrologic or habitat response to shorter-term climatic conditions provides another means of evaluating short-term versus more robust recovery. For this reason, hydrologic data recorded at the Burro Cienaga monitoring sites were evaluated relative to watershed precipitation for the project period 2007–June 2014.

Daily precipitation data from Global Historic Climate Network stations US1NMGR0026 (Silver City 24.1SSW) and USC00299691 (White Signal) for the report period January 2007–June 2014 are graphed in Figure 7. The Silver City 24.1SSW (hereafter, 24.1SSW) station is located in the Burro Cienaga headwaters. The White Signal station is just outside of the Burro Cienaga watershed, about 12 km northeast of 24.1 SSW and slightly east of the Continental Divide. Data from station Silver City 24.1SSW would therefore more nearly represent precipitation in the Burro Cienaga watershed. Linear regression was used to evaluate the relationship between data available from both stations, by month, for the period early November 2008 through November 2012 (*SSW24.1 = 1.3876WhiteSignal - 2.5377*); $R^2 = 0.60$. The White Signal station reports less precipitation on average than station SSW24.1 (Figure 7). However, no data from SSW24.1 were available for January 2007 through early November 2008. White Signal station data were substituted for this early period, but actual headwaters precipitation during this period, which includes about 20 months of the initial monitoring period, may have varied somewhat from the values used in this report.

To clarify variation in watershed precipitation by year and season through the project report period, precipitation values were summed by hydrologic season and by year. Seasonal totals from each year were compared against longer-term average seasonal total precipitation recorded at the White Signal station, from 1981–2010 (Table 1), as no data are available from station SSW24.1 for the longer period.

Precipitation recorded during most of the years 2007–2014 at the GHCN stations generally followed the pattern typical for the southwestern U.S., in which the spring months are driest and summer monsoon months usually the wettest. In some years large, slow-moving tropical fronts move into the region during the late fall/winter months, bringing large amounts of rain and/or snowfall. During the project period 2007–2014, average precipitation during each season except the summer monsoon was lower than the longer-term average (45% to 74%; Table 1). In 2007, precipitation during the winter and summer months was roughly equivalent to the longer-term average (96% and 112%, respectively), but during the spring and fall months was only about 2/3 of the 1981–2010 average. Additionally, precipitation in 2008–2014 was compared against that recorded during the first project year, 2007. In most years, watershed precipitation from October through June of the following year was typically less, and sometimes much less, in 2008–2014 than in 2007, and therefore also well below the longer-term average.

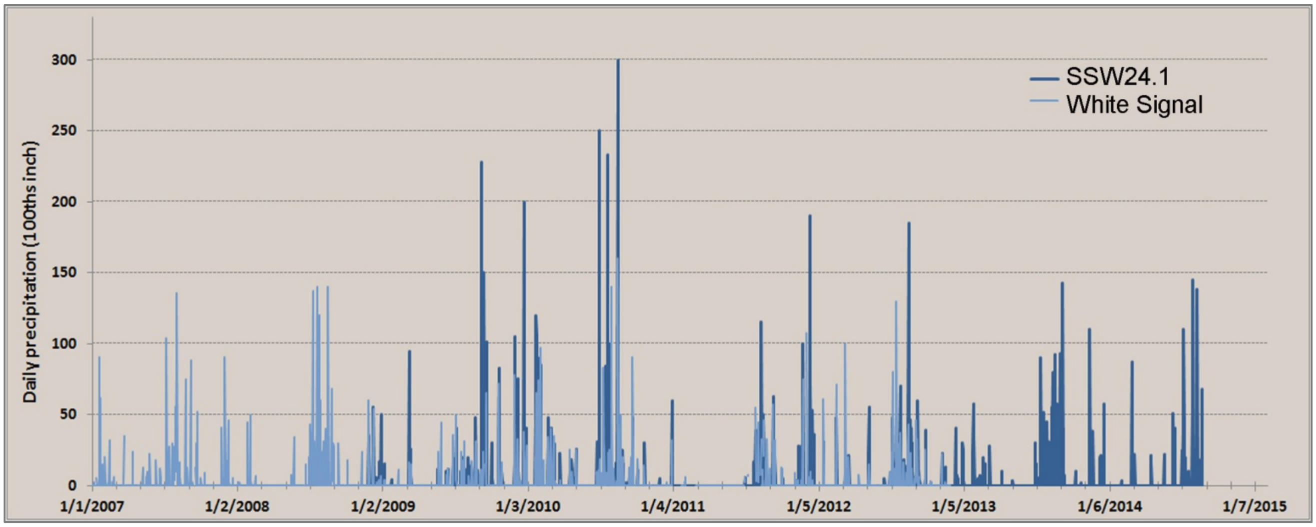


Figure 7. Daily precipitation at GHCN stations at White Signal, NM, and Silver City 24.1SSW, January 2007 through June 2014. No data are available from Silver City 24.1SSW for the period January 2007 through early November 2008, and data from the White Signal station for that period are used in this report. Data from the Silver City 24.1SSW station are used for the remainder of the report period.

Precipitation totals by hydrologic season for each year are graphed as percentage values relative to the baseline year, 2007, in Figure 8. Relative to 2007, Figure 8 shows that less precipitation was recorded during the months of January–March in all following years except 2010. During most of the years 2008–2014, winter precipitation was < 50% that received in 2007, and therefore less than half of the longer-term average for those months. The period from the fall 2009 through winter 2010 (October 2009–March 2010) was the exception, with recorded precipitation more than twice that of 2007. Conditions on the Burro Cienaga watershed therefore resemble those throughout most of the southwestern U.S., where often severe drought conditions have prevailed since 2010.

During the spring months of April–June, precipitation in 2007 was only about 2/3 that recorded on average between 1981–2010, and in 5 of the 7 years following 2007, spring precipitation was even less than in 2007. Conversely, monsoon (July–September) rainfall in 2007 was higher than the longer-term average, and in half of the years between

Table 1. Average total seasonal precipitation at White Signal GHCN station, 1981-2010, and total seasonal precipitation by year, 2007–2014, at the White Signal or Silver City SSW24.1 stations.

	Jan-March		Apr-June		July-Sept		Oct-Dec	
Period	**Total, 100ths in.**	**% of avg.**	**Total, 100ths in.**	**% of avg.**	**Total, 100ths in.**	**% of avg.**	**Total, 100ths in.**	**% of avg.**
1981–2010 average	334	100%	169	100%	796	100%	420	100%
2007	319	96%	112	66%	889	112%	289	69%
2008	114	34%	63	37%	1200	151%	*234	*56%
2009	165	49%	70	41%	811	102%	602	143%
2010	680	204%	117	69%	1367	172%	106	25%
2011	0	0%	0	0%	453	57%	513	122%
2012	117	35%	84	50%	815	102%	135	32%
2013	219	66%	13	8%	1044	131%	288	69%
2014	112	34%	149	88%	n/a	n/a	n/a	n/a
Average, 2007–2014	216	65%	76	45%	**940	118%	**310	74%

% of avg. = Total seasonal precipitation as a percentage of 1981–2010 average seasonal total. Shaded cells are data from the White Signal station; unshaded, from the Silver City SSW24.1 station. *Summed from partial data from both stations; see text for dates. ** 2007–2013 average.

2008–2013, monsoon precipitation was even greater—at least nearly 120% the amount received in 2007. The most extreme exception in this case occurred during the 2011 monsoon, when about half as much rain fell as in 2007. In addition, the 9 months preceding the 2011 monsoon were also exceptionally dry; between January and June 2011, zero precipitation was reported.

The fall months of 2007 were dry relative to the longer-term average, and fall precipitation during 3 of the 6 years following was considerably less than in 2007. Major exceptions occurred in 2011, when fall precipitation totaled 177% that received in 2007, and 2009, with more than twice as much precipitation as in 2007.

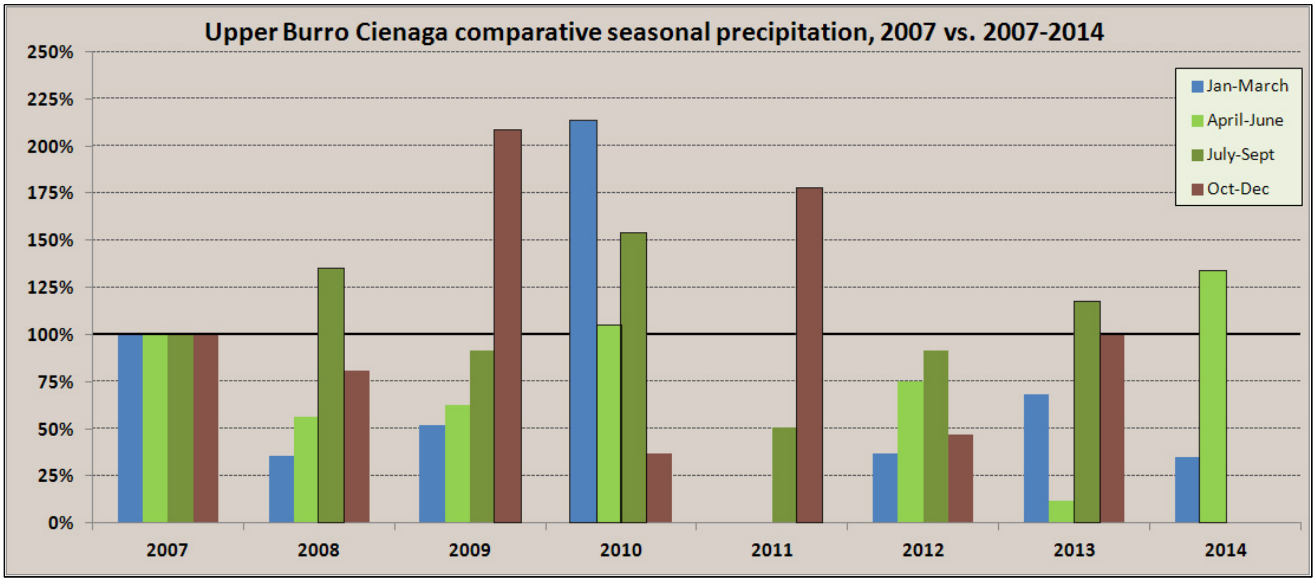


Figure 8. Seasonal annual precipitation totals recorded at GHCN stations White Signal, NM, and Silver City 24.1SSW, for January 2007 through June 2014. Seasonal totals from 2007 are used as "baseline" (100%) values. Following years' seasonal totals are graphed as a percentage of 2007 seasonal totals. Total precipitation recorded during the first six months of 2011 was zero.

Groundwater. Groundwater data recorded on each transect March 2007–June 2014 are shown in Figures 9–11, relative to the channel thalweg elevation as surveyed in 2007 and in 2014. Cumulative daily precipitation recorded at the GHCN climate stations is also plotted on each figure.

The overall hydrological characteristics of the monitoring transects as well as differences among groundwater levels in the floodplain and terrace-level piezometers on each transect appear in the graphs. Piezometers are lettered from left to right facing downstream. On all graphs, a steep vertical *decline* in groundwater level marks a date when the piezometer was purged (to remove sediment potentially clogging the well screen), and the rate of groundwater recharge is evident in the shape of the curve afterwards. For instance, on transect P1 (Figure 9), the rate of recharge in piezometer P1a, installed through dense silt and silt/clay on the left terrace, was much slower than in P1d, a shallow piezometer installed in gravelly sand on the right floodplain.

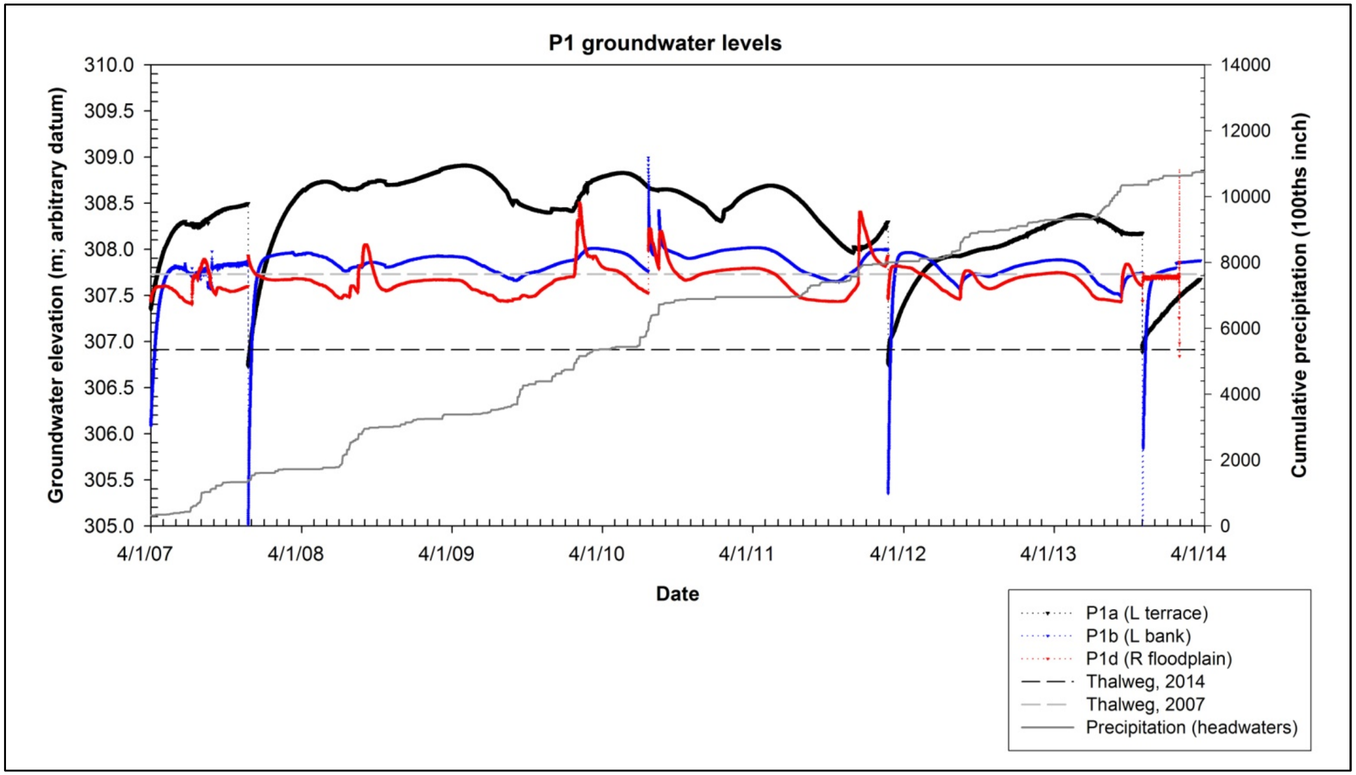


Figure 9. Water levels recorded in 3 piezometers on the P1 transect April 2007 through March 2014, plotted with cumulative daily precipitation. Dashed lines show the channel thalweg elevation, as surveyed in 2007 and 2014, relative to recorded water levels. The original P1a transducer failed in December 2013, and the P1d transducer in February 2014.

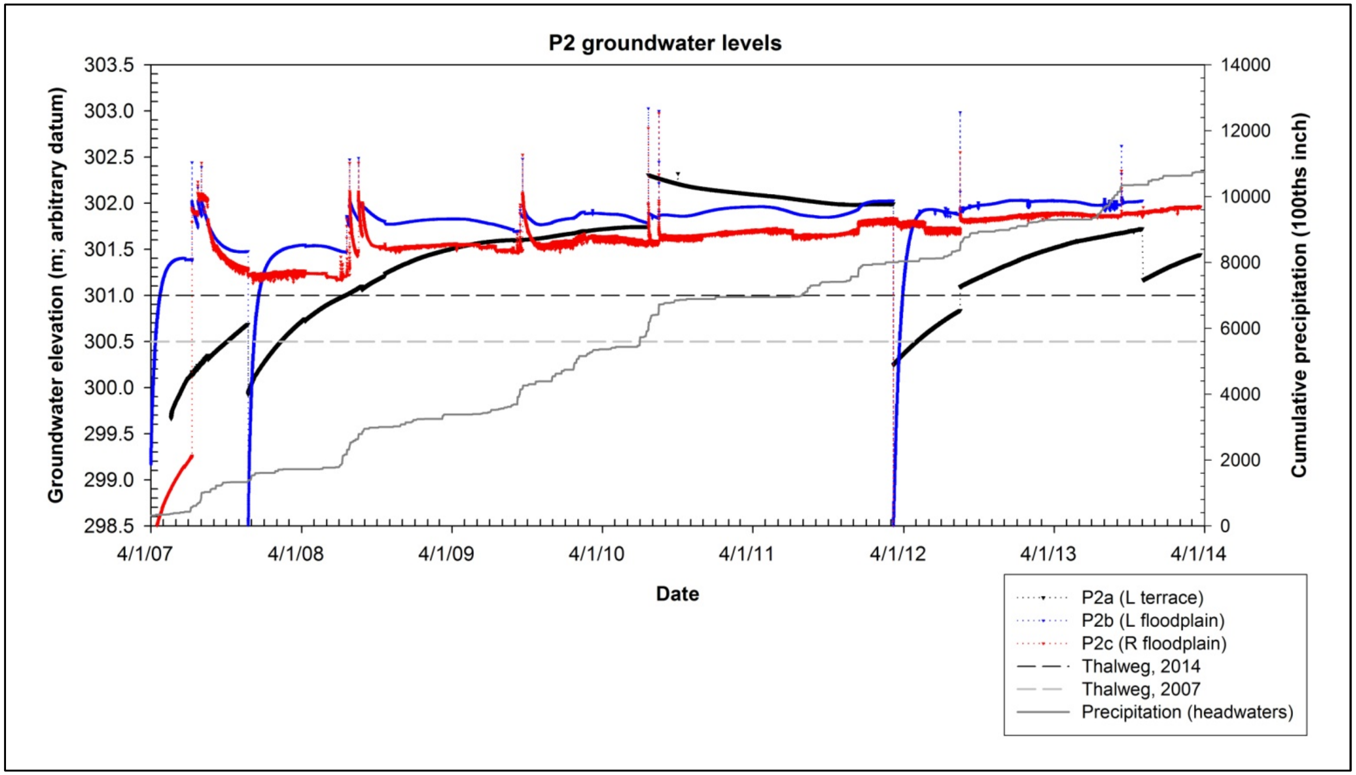


Figure 10. Water levels recorded in 3 piezometers on the P2 transect April 2007 through March 2014, plotted with cumulative daily precipitation. Dashed lines show the channel thalweg elevation, as surveyed in 2007 and 2014, relative to recorded water levels. The original P2b transducer failed in December 2013.

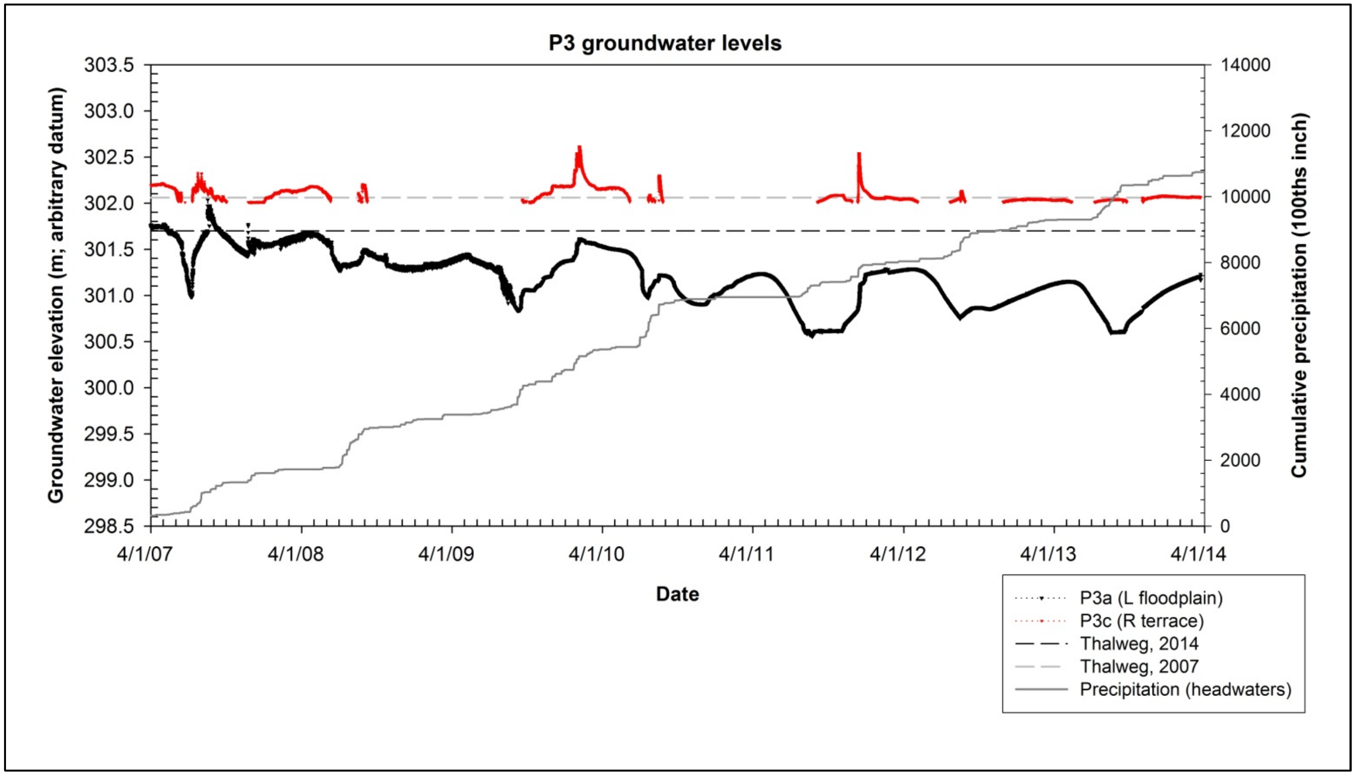


Figure 11. Water levels recorded in 2 piezometers on the P3 transect April 2007 through March 2014, plotted with cumulative daily precipitation. Dashed lines show the channel thalweg elevation, as surveyed in 2007 and 2014, relative to recorded water levels. Transducers in P3b (a piezometer installed on the left floodplain) failed to report sufficient reliable data for this evaluation, and those data are excluded from the graph.

Transect P1 (Figure 9) was established through a zone where Cienaga Spring emits perennial seepage through the left channel bank. The spring's effects are most visible in the relatively stable groundwater levels recorded in both P1a, on the left terrace, and in P1b, installed directly into the seepage zone on the left bank. On this transect, groundwater levels slope from left to right; regional groundwater emitting from Cienaga Spring may move toward the channel from higher-elevation areas due north of transect P1 (Map 4). An overall seasonal pattern of declining groundwater levels was most evident during the months of June–July; groundwater levels tended to slowly rise during the late winter months. Groundwater levels in all piezometers rose and fell after many increased surface flow events; because no surface flow record exists, it is impossible to say with certainty whether every high flow event elevated groundwater levels. Water levels in P1d, the piezometer installed on the right floodplain (Figure 2a), responded most rapidly to flow events; what was probably the largest flood during the project period, in August 2010, appeared to have reached high enough stage to overtop the P1b piezometer as well.

Daily precipitation data and water levels recorded at the P2 transect (Figure 10) suggest that another high-magnitude event occurred August 16, 2012. It may have been during this flood that the perennial pool created on the P1 transect between the 2007 and 2014 surveys was scoured (Figure 5a). The accompanying decrease in channel thalweg elevation created this perennial pool; note that although groundwater levels in P1d remained relatively consistent through the report period and were typically *below* the channel thalweg elevation in 2007, groundwater elevation in P1d is now consistently higher than the channel thalweg. The pool was at least 0.5 m deep during even low flow periods through mid-2014.

At transect P2 (Figure 10), any pattern of seasonal change in groundwater levels appears considerably more subtle than on transect P1. Piezometer P2a was installed on the left terrace through dense silt and silt/clay similar to substrate at P1a. Groundwater recharge to this piezometer post-purging was extremely slow but appeared to stabilize at, or slightly above, groundwater levels in P2b, on the left floodplain surface more than a meter below terrace level. However, groundwater levels in the terrace piezometer did rise in response to major flow events; i.e., in August-September 2010 and August 2012.

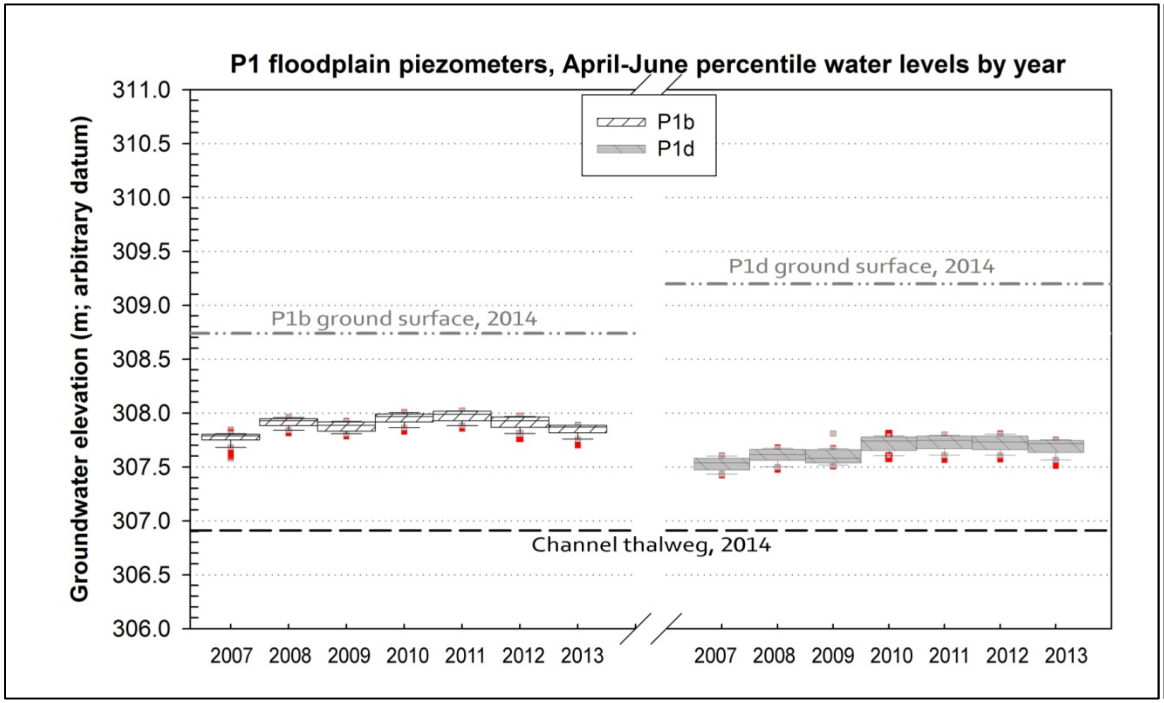
Perennial flow is present in this subreach, and water levels in both floodplain piezometers (P2b and P2c) appear stable over time, although both respond strongly but briefly to high flow events. The channel here has aggraded by 0.5 m since 2007, and groundwater levels in both floodplain piezometers also appear to be rising over time.

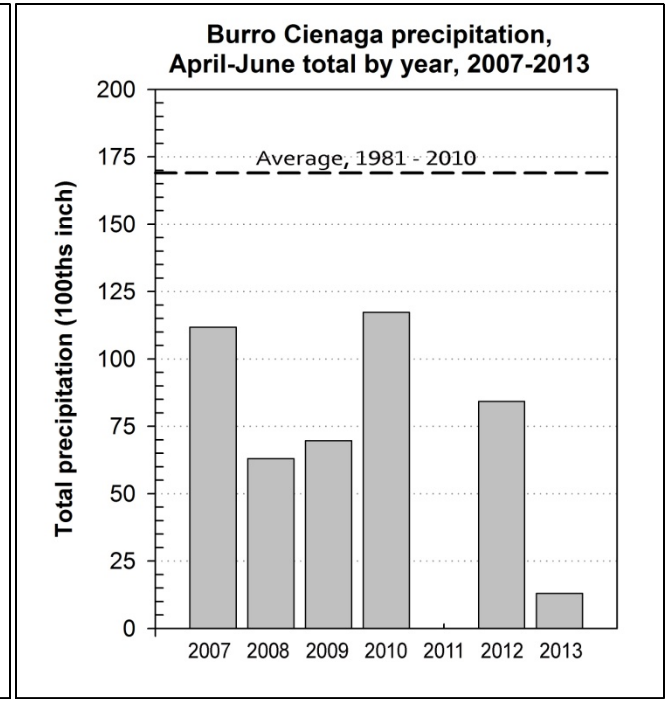
Transect P3 (Figure 11) is downstream of the historic cienaga, and close to the upstream end of the reach where surface flow is intermittent or ephemeral for the remainder of its course through the Pitchfork Ranch. Substrate here is much coarser than at P1 or P2 and no riparian vegetation is present on the transect (Map 4). Although 3 piezometers were installed and instrumented on the transect, data from the transducer in P3b were frequently corrupted and unreliable, and so were not used for this report. Groundwater was present in the P3a floodplain piezometer throughout the project period, but in P3c, installed on the high right terrace, groundwater levels often dropped below recordable levels. The data from P3a show a rough pattern of seasonal fluctuation similar to that at P1, although the steepest decline in water levels generally occurred slightly later at P3 than at P1—in July, rather than June. On average, water levels in P3a were about 0.5 m lower than those recorded in P3c, and the groundwater (and perhaps underlying bedrock) appears to slope from right to left at this transect. Groundwater levels appear to have responded to high flow events, although most sharply in P3c. Groundwater both rose and declined more slowly in P3a following the apparent flow events. Although P3c is positioned on the high right terrace, it is also 15 m nearer the channel than P3a, suggesting that surface flow rapidly infiltrates, and drains from, coarse materials in the high right bank.

To better evaluate any groundwater response to climate conditions or restoration work, data from floodplain piezometers on each transect that were recorded annually during two growing season periods were examined. Seasonal periods correspond to those used to evaluate quantify annual variations in precipitation during the project period. Data from the terrace piezometers were excluded to avoid incorporating the effects of extremely slow groundwater recharge in P1a and P2a in the analysis. Growing season data are those most relevant to riparian and wetland vegetation vigor and reproduction.

Selecting these two periods (April–June and July–September) also excluded most short-term effects of post-purging recharge in the floodplain piezometers; purge visits occurred in February, March, or December. Recharge in April 2007, immediately after the piezometers were first installed and purged, was very slow even in some floodplain piezometers. Where these effects significantly influenced the resulting statistics, they are noted. In addition, complete recharge in piezometer P2b after purging in March 2012 was much slower than in P2c, continuing through April 2012 (Figure 10). In order to include data from P2b in the analysis, the relationship between water elevations in P2c and P2b for the period May 15–June 15, 2012 was calculated by linear regression [$P2b = (P2c * -0.2023) + 362.98$; $r^2 = 0.67$]. The resulting equation was applied to all P2c water elevations from April 1 through May 31 to estimate true groundwater elevations levels at P2b. Differences between all estimated water elevations and the actual water levels recorded in P2b for the last two weeks of that period (May 15–May 31) were less than 1 cm. Groundwater elevations at P2b calculated from the equation were substituted for recorded water levels during the recharge period April 1–May 15, 2012 for the analysis.

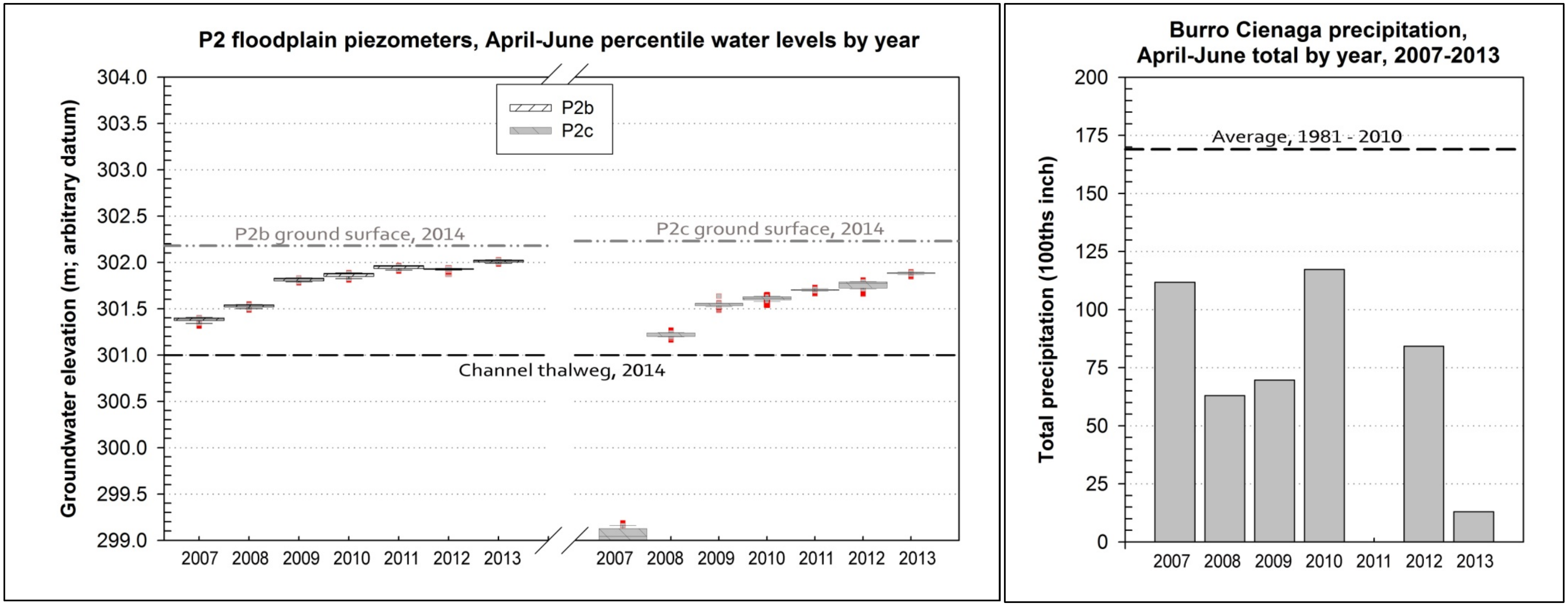
Box plots were created of groundwater elevations for each period and examined relative to annual differences in precipitation, and for trends in groundwater elevation over time. Each box outlines 25th and 75th percentile groundwater elevations; median elevation plots as the horizontal line though each box. The 10th and 90th percentile values are depicted by whiskers, and all outlier values are plotted as red squares. Ground surface and channel thalweg elevations as of 2014 are also plotted on each figure for reference. Figures 12a, 13a, and 14a show the resulting box plots from the floodplain piezometers during the April–June period each year 2007–2013; each is accompanied by the graph of total precipitation during the same period each year for comparison (Figures 12b–14b).





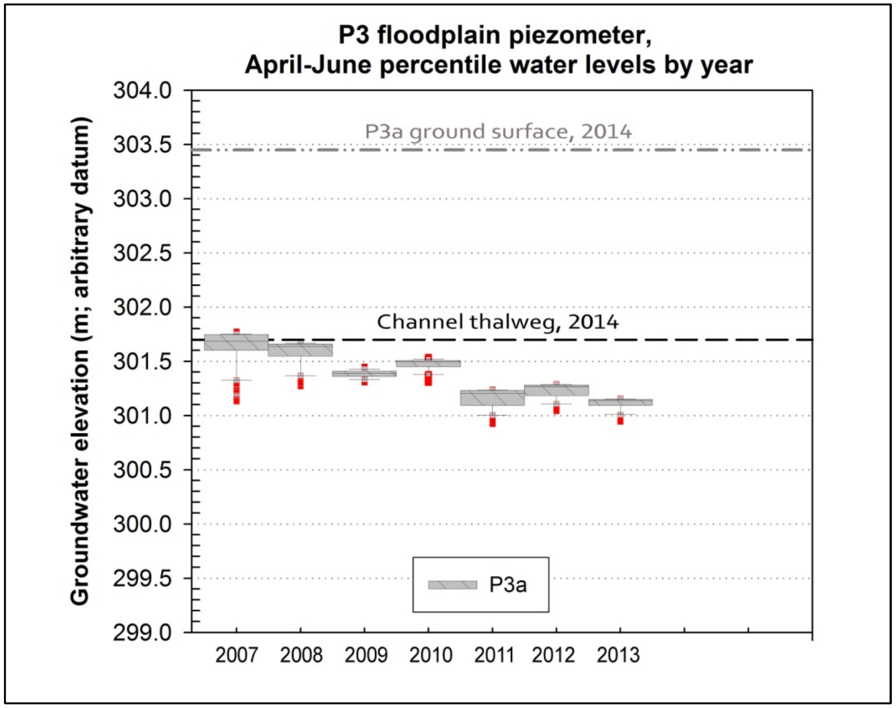
Figures 12a (left) and 12b. 12a: Percentile groundwater levels relative to channel thalweg and piezometer ground surface in two floodplain piezometers on transect P1 during April–June, 2007 through 2013. Water levels in P1b, where Cienaga Spring emits surface seepage through the channel bank, are on the left, and in P1d, on the right floodplain, on the right. Each box plot depicts all water levels recorded during the 3-month period by year shown on the *x* axis.

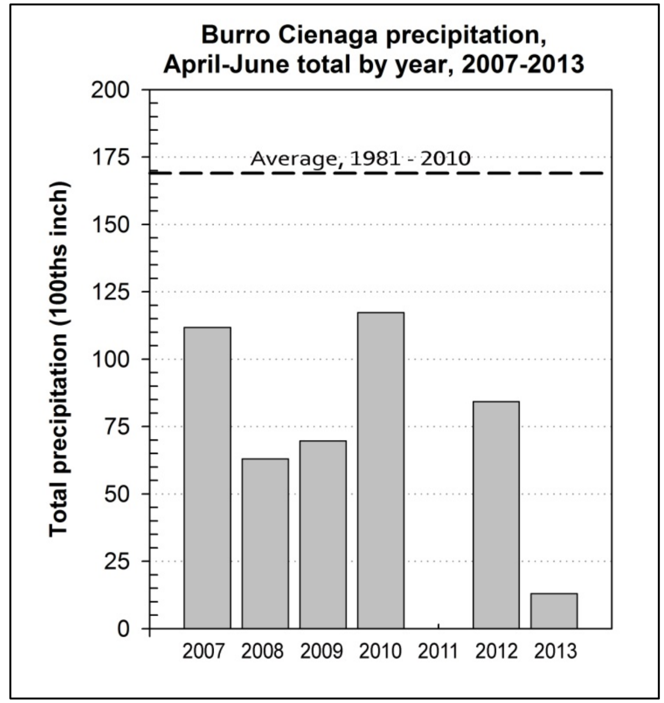
12b: Total precipitation recorded annually from April–June, at the White Signal or Silver City SSW24.1 GHCN stations, 2007 through 2013. The dashed line shows average total precipitation for the same 3 months, 1981–2010.



Figures 13a (left) and 13b. 13a: Percentile groundwater levels relative to channel thalweg and piezometer ground surface in two floodplain piezometers on transect P2 during April–June, 2007 through 2013. Water levels in P2b, on the left floodplain, are on the left, and in P2c, on the right floodplain, on the right. Each box plot depicts all water levels recorded during the 3-month period by year shown on the *x* axis.

13b: Total precipitation recorded annually from April–June, at the White Signal or Silver City SSW24.1 GHCN stations, 2007 through 2013. The dashed line shows average total precipitation for the same 3 months, 1981–2010.





Figures 14a (left) and 14b. 14a: Percentile groundwater levels relative to channel thalweg and piezometer ground surface in one floodplain piezometer on transect P3 during April–June, 2007 through 2013. Piezometer P3a is on the left floodplain. Each box plot depicts all water levels recorded during the 3-month period by year shown on the *x* axis.

14b: Total precipitation recorded annually from April–June, at the White Signal or Silver City SSW24.1 GHCN stations, 2007 through 2013. The dashed line shows average total precipitation for the same 3 months, 1981–2010.

Groundwater–precipitation relationships: April–June. The spring months of April–June are typically the driest of the year (Table 1), and thus surface runoff tends to have the least effect on groundwater levels during this period. Although these months mark the beginning of the annual growing season, average temperatures remain cool through the early part of the season, and full leaf-out on most riparian species does not occur until mid-May. As a consequence, rates of evapotranspiration and the associated drawdown of groundwater levels also accelerate as the season progresses.

P1. Groundwater levels on each transect during the months of April–June responded differently over time. At transect P1 (Figure 12), groundwater levels from April–June were lowest in 2007, the first project year. Recorded water levels in P1b from April–June are somewhat artificially depressed by slow recharge following installation (water levels during initial recharge appear as outliers below the box); this effect appears slight, however, as groundwater infiltrated piezometer P1d almost immediately, and P1d water levels were also lowest in 2007.

Longer term, regional climate patterns are likely to be more evident at this transect (and especially at piezometer P1b) than at P2 or P3, because of its position at a site of emission for Cienaga Spring. Spring seepage is crucial to perennial flow within this subreach; the streambed is usually dry for at least ½ mile upstream of this point. The groundwater data reflect the strong influence of spring seepage at this transect. April–June groundwater levels after 2007 in both piezometers remained relatively consistent, with 90% of all recorded water levels varying within less than 0.3 m. Median values were generally shifted toward the upper edge of each box (i.e., were higher than mean values), suggesting that steady flow sustained high groundwater levels at this site during these months. Upper outlier values show the brief rises in groundwater levels that occurred during slightly elevated surface flow events, but otherwise scant relationship with concurrent precipitation totals (Figure 12b) is evident.

Groundwater levels rose in 2008 but fell slightly in 2009, although April–June precipitation was similar in both years. They rose again in 2010, the wettest April–June of the project period. They were slightly higher still in 2011, despite zero precipitation during the entire first half of that year. In fact, the highest April–June groundwater levels of the project period were recorded in 2011. This may reflect a delayed groundwater response at Cienaga Spring itself to the previous year's relatively wet monsoon (July–September 2010; see Figure 8), the effects of channel aggradation on increased groundwater storage, or some combination of those. In both piezometers, water levels fell slightly in 2012, although the median decline was greater in P1b than in P1c. Again, this may reflect delayed flow path response to the dry 3 months previous. However, an even larger decline occurred in 2013 in both piezometers; possibly resulting from channel scouring on the transect that created the deep pool mapped in 2014, but not present in 2007. (Lacking interim geomorphic data, it is impossible to say precisely when after 2007 this pool was created.) On the other hand, while pool scouring deepened the channel on the transect by nearly a meter, median April–June groundwater levels declined less than 0.2 m between 2012–2013.

The most significant aspect of the April–June groundwater data at transect P1 is probably their constancy. Despite the overall paucity of precipitation during the spring months for all years 2007–2014 (relative to the longer term average), P1 groundwater levels during these months remained relatively constant throughout the project period .The landowners report that channel incision throughout the upstream-most reach was actively ongoing when restoration work began in 2005. This has ceased. Lacking 2005 geomorphic data, the total amount of aggradation at and near transect P1 since work began cannot be quantified. However, some deposition has been documented just upstream of the transect even since 2007.

P2. As at P1, floodplain piezometers at P2 showed little daily fluctuation in groundwater levels during April–June, with 75% of water levels most years recorded within a range of about 10-15 cm, and all within a range of < 0.4 m. Median groundwater levels at this transect were also shifted toward the upper edge of each box plot, reflecting the site's perennial flow. Also as at P1, water levels recorded in both floodplain piezometers was lowest in 2007, and in P2b were somewhat depressed by the initial delay in recharge. In P2c, initial recharge was exceedingly slow (bottom of graph); after a flood in July 2007, however, recharge in this piezometer was rapid.

After 2007, the pattern of April–June groundwater levels at P2 was strikingly different than those recorded at P1. Groundwater levels rose almost continuously after 2007, with the largest single year-to-year increase occurring between 2008–2009. Except in 2012, year-to-year changes in water levels in both piezometers were quite similar. In 2012, P2b recorded groundwater levels fell slightly from those in 2011, and fluctuated within the tightest range of any project year; but in P1c, 2012 April–June groundwater levels showed the *greatest* fluctuation of any year, and rose slightly from 2011 levels. Likely explanations for this difference may be differential deposition over time, raising the left channel bank above high flows that overtopped the right floodplain; or hinge-felling of trees that temporarily slowed and re-directed overbank flows toward the right floodplain. Although substantial deposition since 2007 was documented on both sides of the active channel in 2014 (Figure 2b), it was of different form on each side. On channel left (at P2b) deposition widened the channel bank toward the right (effectively increasing the volume of bank material through which groundwater must travel to reach piezometer P2b); on the right, deposition simply raised a relatively flat floodplain surface. A lack of interim geomorphic data hampers full interpretation of this situation.

There appear to have been few even moderately elevated flow events in late 2012–mid 2013, and both P2b and P2c recorded only minor fluctuations in groundwater levels. At both piezometers, however, groundwater levels again rose in 2013, despite relatively dry conditions throughout most of the previous year. Overall, by April–June 2013, median water levels at P2b were nearly 0.5 m higher than in 2008, and at P2c, more than 0.3 m higher.

A relationship between rising groundwater levels and sediment capture is seldom as clear as that documented at transect P2 during the project period. Substantial channel deposition was documented at, and importantly, *upstream* of, the P2 transect between 2007 and 2014. Deposition averaged 0.3 m through a subreach about 80 m long (Figure 5a). Deposition was not confined within the active channel. At the transect, deposition mapped on the channel banks and floodplain ranged from 0.3 to 0.5 m thick. For alluvial groundwater storage, the fine-grained composition of those sediments is equal important. At the transect, and through most of the subreach, a thick carpet of alkali muhly and other grasses trapped fines, ranging from silty to sandy loam, during overbank flows. The roughness introduced by the presence of dense, low growing vegetation attenuates flood energy, while in the channel, the combination of downed material and herbaceous wetland species performs the same function. Groundwater moves through fine substrate much more slowly than through coarser sands and gravels, and capillary action is improved. This combination of factors creates a feedback loop in which alluvial groundwater is stored for longer periods, providing a robust environment for the rhizomatous root systems of floodplain grasses, which in turn stabilize and capture additional fine sediments during flood events. Groundwater stored in the alluvial floodplain is released slowly during low flow periods. As a consequence, both the extent and duration of surface flow in the channel farther downstream during dry periods should increase.

P3. Recorded groundwater levels for April–June at transect P3, downstream of the historic cienaga area, differed from those at either upstream transect. Of the three transects, only groundwater levels at P3 corresponded with precipitation for the same period each year. Median water levels were higher than the mean in most years, again showing that high flow events during these months had less influence on groundwater levels than did a seasonal decline in the months of May and June typical of this transect.

Comparatively little restoration work has been completed in this subreach (Map 3). Obligate wetland species now occupy a small pool upstream of the transect; riparian species are scattered and limited to banks immediately adjacent to the channel. While the extent and density of native grass cover across the floodplain has increased since 2007, vegetation remains relatively sparse, and little fine sediment is captured during overbanking flows. When elevated flows do recharge alluvial groundwater, it therefore continues to drain rapidly through coarse floodplain substrate of sand and gravel. The highest groundwater levels recorded during these months remained 1.5 to 2 m below ground surface, one reason for the rarity of cottonwood or willow recruitment in this subreach. In years when seedling establishment does occur, chances are high that groundwater levels will rapidly recede below the reach of their growing root systems, with desiccation and mortality the result.

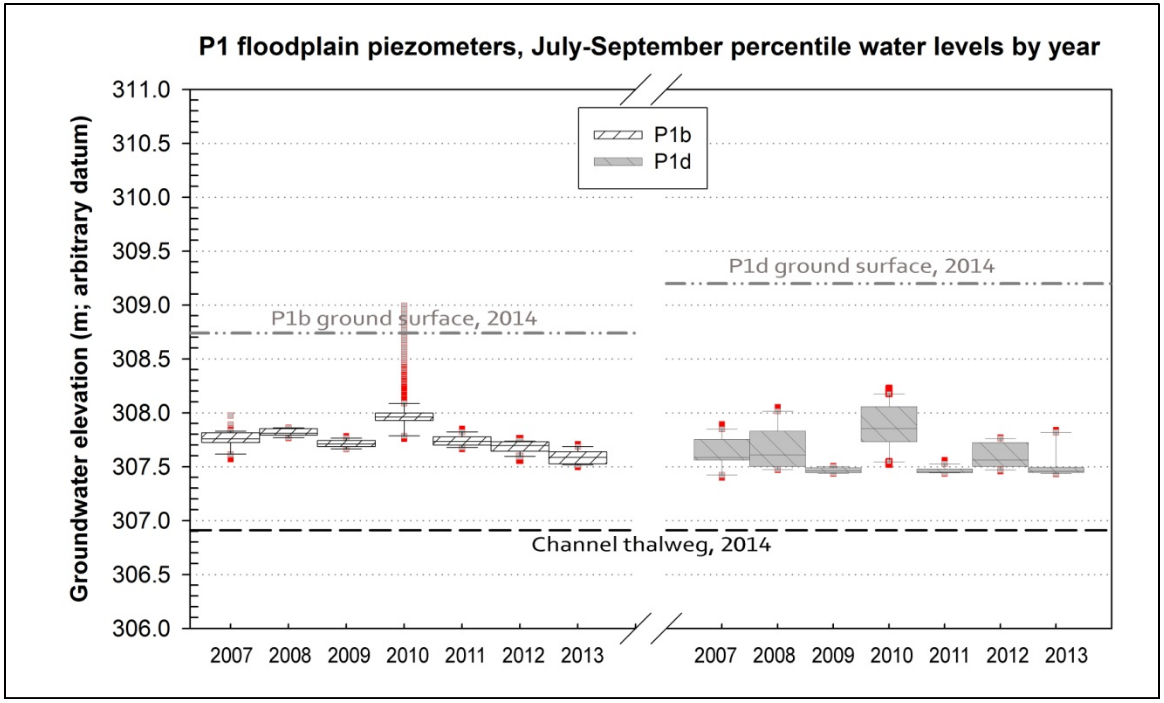
In the baseline year of 2007, water levels in piezometer P3a stabilized immediately after installation, and were therefore not affected by slow recharge. Rather the broad variation (0.8 m) of water levels in April–June that year, including the very low levels recorded as outliers, reflects the steep decline in groundwater levels that began in May that year. Precipitation during the previous three months, January–March, was near the long-term average, but from April–June, only about 70% of average (Table 1).

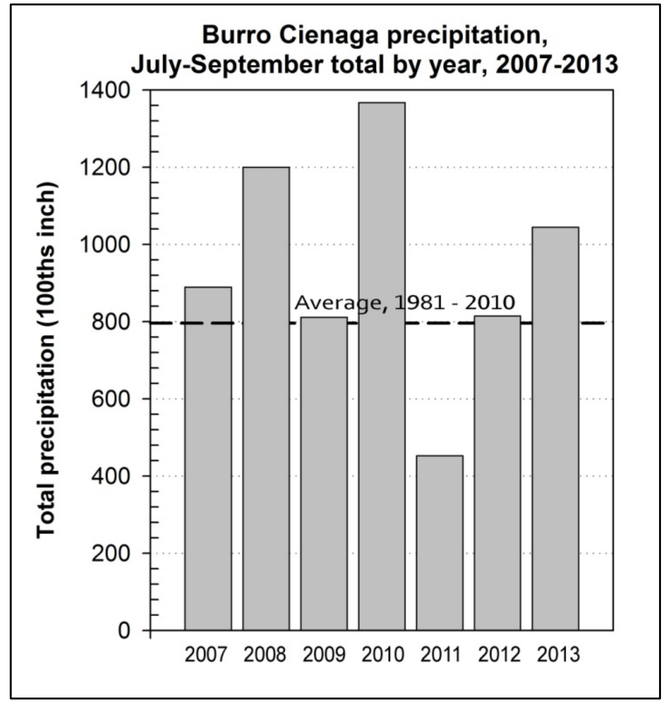
After overall declines in springtime groundwater levels in both 2008 and 2009, median groundwater levels recovered to within approximately 0.2 m of their 2007 elevation after the wet winter of 2010. The largest decrease in April–June groundwater levels occurred between 2010 and 2011; the driest winter and spring months of the project period also occurred in 2011. Water levels in the two years that followed, 2012 and 2013, mimicked spring precipitation each year, rising in 2012 and then declining to the lowest levels of the project period in 2013.

Groundwater–precipitation relationships: July–September. Box plots of annual floodplain groundwater levels at each transect during the monsoon period of July–September were also created (Figures 15a, 16a, and 17a). Again, each box outlines 25th and 75th percentile groundwater elevations; median elevation plots as the horizontal line though each box. The 10th and 90th percentile values are depicted by whiskers, all outlier values by red squares, and the ground surface and channel thalweg elevations as of 2014 are also plotted on each figure. Each figure is again accompanied by the graph of total precipitation during the same period each year for comparison (Figures 15b–17b).

P1. The monsoon period, July through September, is typically the period not only of greatest total rainfall, but also when the greatest number of precipitation events occur each year. Monsoon season therefore usually generates more high flow events than other periods. P1 groundwater levels (Figure 15a) resembled seasonal precipitation totals slightly more during each year's monsoon than during the drier spring months—at least until 2012. P1b water levels again varied less overall than those at P1d, even in 2010, when a single extreme high flow overtopped the P1b piezometer. Median water levels in P1b were equal to or slightly greater than average water levels each year. In P1d, however, mean water levels during the monsoon period were substantially higher than median levels in 4 of the 7 years. In other words, the difference between groundwater levels during low flows and those during flood events was great enough to raise the average water level above half of all recorded water levels at P1d, but not at P1b. At P1d, groundwater levels varied over a greater range in all years when above-average monsoon rainfall occurred, except 2013. Declining water levels in piezometer P1b that year suggest either the effects of channel scouring on surface water levels during low flow periods, of extended drought on rates of seepage from Cienaga Spring, or both. At P1d, groundwater levels remained low throughout the monsoon in 2013 except for a brief rise during what was likely a single flow event. A single high flow probably occurred in September that year, after nearly 3.5 inches of rainfall was recorded between August 20 and September 9.

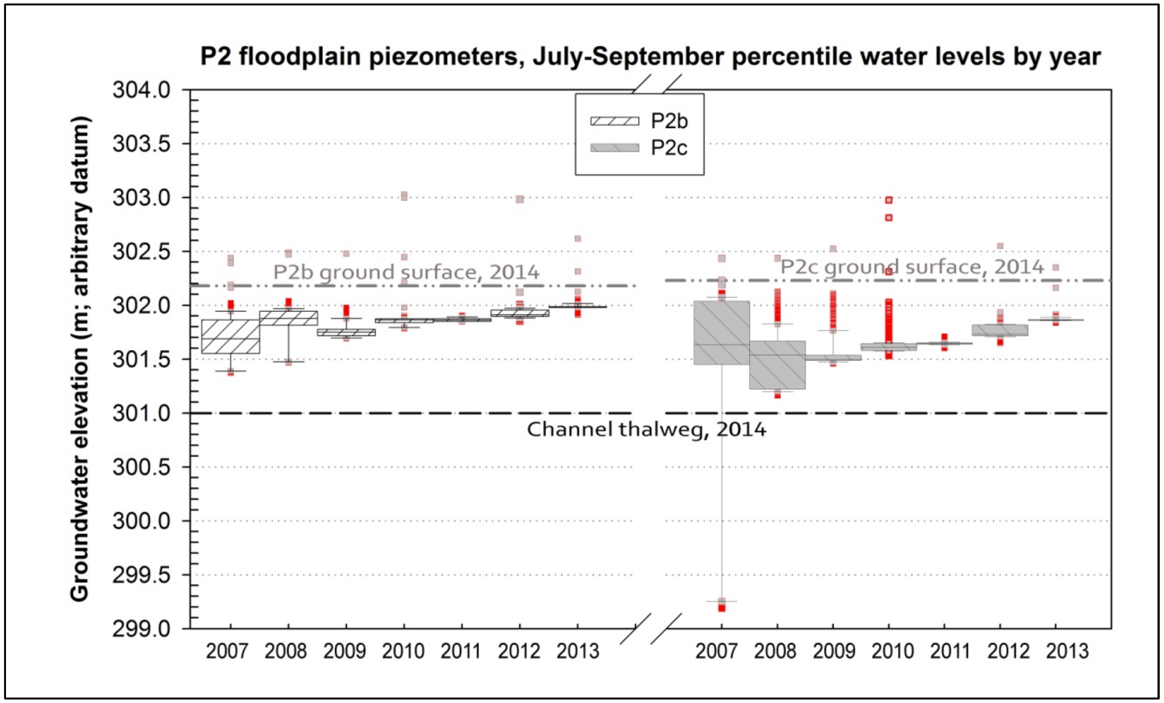
P2. The most significant result from the transect P2 monsoon season data (Figure 16a) is that, after 2009, July–September groundwater levels at the transect showed the same rising trend over time as those recorded during the spring months. (The very low outliers recorded in 2007 for P2c again reflect its very slow rate of initial recharge; its water level abruptly increased during a flood event on July 10 and it appeared to respond rapidly to changing water levels thereafter.) In all years except 2011, a number of high groundwater events registered in both piezometers, but variation within 75% of all water levels recorded each year after 2008 was less 0.25 m. While the lowest groundwater levels recorded in both piezometers rose each year after 2008, median monsoon water levels declined slightly in 2009 from those recorded in 2008. Thereafter, median levels in both piezometers rose in all years except 2011, when only P2c registered higher water levels than during the 2010 monsoon period. P2b median groundwater levels in 2011 were the same as those recorded during the 2010 monsoon. However, the 2011 monsoon period was the driest of all during the project period, and zero precipitation was recorded during the 3 months previous (Figures 13b and 16b).

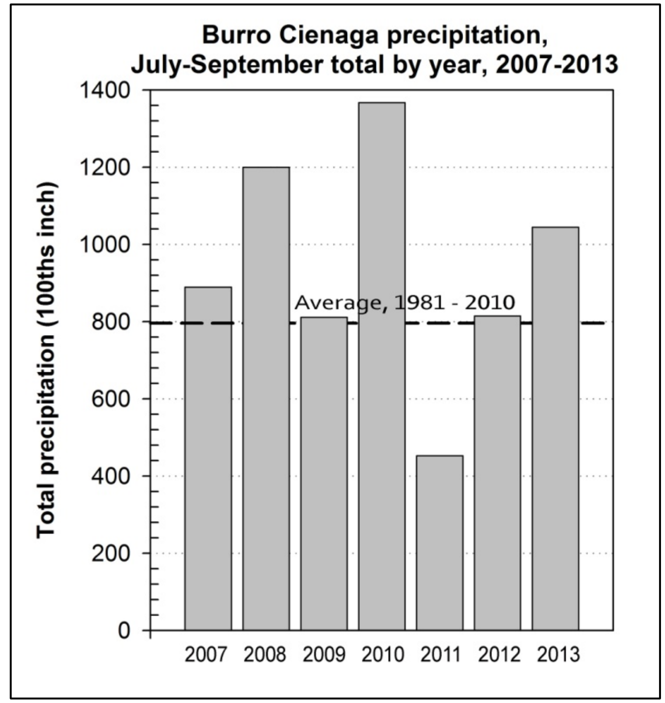




Figures 15a (left) and 15b. 15a: Percentile groundwater levels relative to channel thalweg and piezometer ground surface in two floodplain piezometers on transect P1 during July–September, 2007 through 2013. Water levels in P1b, where Cienaga Spring emits surface seepage through the channel bank, are on the left, and in P1d, on the right floodplain, on the right. Each box plot depicts all water levels recorded during the 3-month period by year shown on the *x* axis.

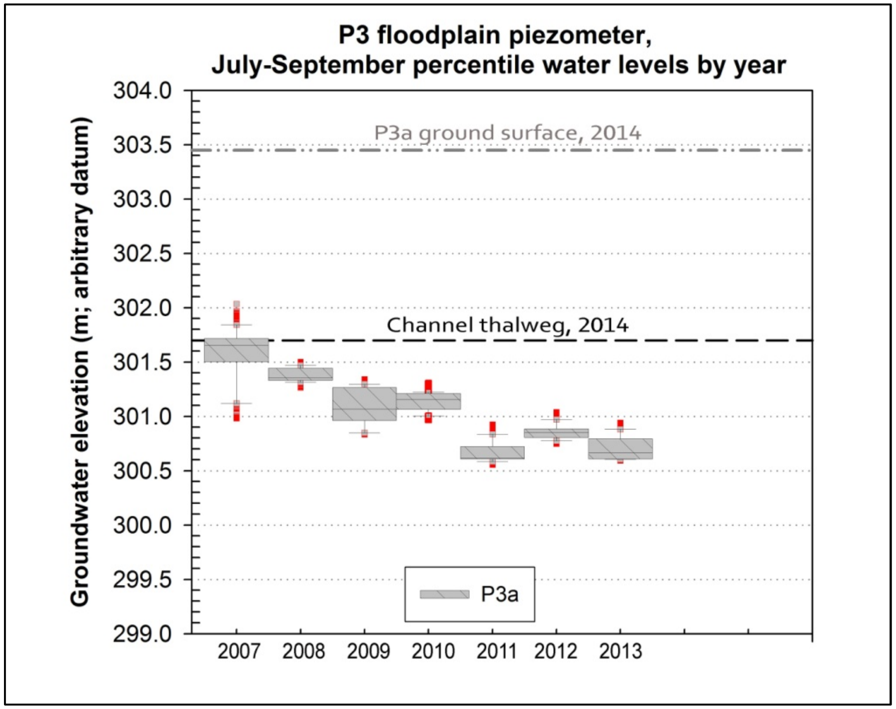
15b: Total precipitation recorded annually from July–September, at the White Signal or Silver City SSW24.1 GHCN stations, 2007 through 2013. The dashed line shows average total precipitation for the same 3 months, 1981–2010.

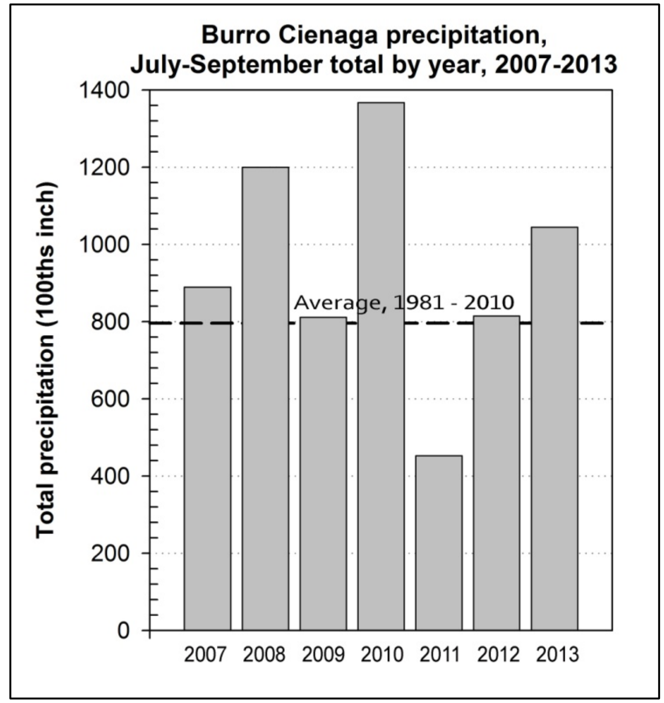




Figures 16a (left) and 16b. 16a: Percentile groundwater levels relative to channel thalweg and piezometer ground surface in two floodplain piezometers on transect P2 during July–September, 2007 through 2013. Water levels in P2b, situated on the left floodplain, are on the left, and in P2c, on the right floodplain, on the right. Each box plot depicts all water levels recorded during the 3-month period by year shown on the *x* axis.

16b: Total precipitation recorded annually from July–September, at the White Signal or Silver City SSW24.1 GHCN stations, 2007 through 2013. The dashed line shows average total precipitation for the same 3 months, 1981–2010.





Figures 17a (left) and 17b. 17a: Percentile groundwater levels relative to channel thalweg and piezometer ground surface in one floodplain piezometer on transect P3 during July–September, 2007 through 2013. P3a is situated on the left floodplain. Each box plot depicts all water levels recorded during the 3-month period by year shown on the *x* axis.

17b: Total precipitation recorded annually from July–September, at the White Signal or Silver City SSW24.1 GHCN stations, 2007 through 2013. The dashed line shows average total precipitation for the same 3 months, 1981–2010.

P3. In complete contrast to the response at P2, monsoon groundwater levels in piezometer P3a (Figure 17a) showed an overall decline between 2007–2013, as well as little relationship with annual monsoon precipitation totals. During the very wet monsoon of 2010, its median groundwater level rose slightly from those recorded in 2009, but then fell more than 0.5 m in 2011. Water levels rose again in 2012, when total monsoon precipitation was twice that received in 2011—although still only about the longer-term average. However, despite the 2012 increase in median water level, it remained nearly 1 m lower than that recorded in 2007. Monsoon precipitation in 2013 was greater than in 2012, but the P3a median water level dropped again in 2013, in this case about 0.2 m.

The channel at transect P3 incised approximately 0.5 m between 2007 and 2014, a change that would decrease the level at which surface flows recharged groundwater in channel banks and floodplain. However, groundwater levels at this transect also appear more strongly influenced by two climate-driven factors than those at P1 or P2. Antecedent conditions, including total precipitation during the three months previous, may strongly affect most P3a water levels during each year's monsoon period. For example, monsoon precipitation in 2008 was 50% higher than the long-term average and nearly 40% greater than in 2007, but P3a median water level recorded during the 2008 monsoon was 0.3 m lower than in 2007. However, during the months of April–June, total precipitation in 2008 was only about half that of the same months during the previous year (Figure 14b). Similarly, P3a monsoon water levels in 2013 were lower than those in 2012, despite above-average monsoon rainfall, but the spring months of 2013 were extremely dry. At this site, where groundwater drains rapidly through coarse alluvium, the effect of limited surface flow caused by below-average precipitation is a steady, often steep decline in groundwater levels. As a consequence, water levels after a very dry spring season begin the early monsoon from a substantially lower elevation than after a wetter one. The effect during long-term, regional drought conditions is cumulative; the volume of alluvial recharge required to replenish groundwater to pre-drought levels increases every year.

Thus the second factor, composed of both surface flow duration and timing, becomes increasingly significant during such periods. Sustained and substantial increases in groundwater levels under the conditions present at transect P3 require not only a single season of above-average rainfall, but either a large number of surface flow events, elevated surface flows of long duration, or both. These elements were seldom present between 2007 and 2014. The lack of fine substrate, one effect of infrequent overbank flows and sparse vegetation, in turn hampers recruitment of floodplain vegetation that would help capture these finer particles. Restoration work aimed at creating conditions to enhance such deposition is in its early stages in this subreach. The P3 2007–2014 data therefore provide a valuable baseline for measuring the effectiveness of this work.

Conclusions

Although the monitoring project described in this report focuses on historic wetland and riparian zones within the Burro Cienaga watershed, it is important to reiterate that the ecosystem restoration goals of the Pitchfork Ranch land owners are set at the landscape scale. Upland restoration work is actively ongoing, but not monitored directly by this project. Yet upland restoration will affect conditions in the riparian and wetland ecosystems, as they form, after all, the zone to which the entire watershed drains. Even within the Burro Cienaga corridor, restoration goals extend far beyond the cienaga wetland ecosystem. Larger-scale goals include 1) recreating conditions in which the upper stream and wetland are able to more effectively capture and store alluvial groundwater for longer periods, slowing its release downstream; 2) extending the availability of surface or near-surface water to increase habitat diversity throughout the Burro Cienaga corridor; and 3) re-establishing riparian "micro-systems" within areas where xeric conditions resulted from decades of land use practices across the watershed. While geologic controls (e.g., zones of shallow underlying bedrock that support near-surface groundwater levels) no doubt play an important role in the long-term viability of these micro-systems, restoration work enhances their capacity to do so.

Hydrologic monitoring at the Pitchfork Ranch augments the qualitative monitoring of annual repeat photography. Its goal is to quantify long-term effects on channel and floodplain morphology, and on alluvial groundwater storage, relative to restoration efforts. Collection of continuous groundwater data enables evaluation of groundwater levels relative to both short-term and long-term climate conditions. Geomorphic data collection was quite limited in scale and frequency by project constraints. Nonetheless, even the two data sets available provide essential documentation of changing conditions and therefore, a means by which highly variable responses in alluvial groundwater levels can be more clearly and correctly interpreted. The results of both qualitative and quantitative data collection show that:

- There is no perennial surface flow in the Burro Cienaga streambed for at least 800-1000 m upstream of the Cienaga Spring seepage zone near the upstream Pitchfork Ranch boundary. Discharge from Cienaga Spring supports perennial surface water in the historic wetland area, and is probably reduced during extended, severe drought periods.
- Restoration work appears to have arrested channel instability and headcut development after 2005 that otherwise would have resulted in further desiccation of the riparian/wetland corridor upstream of the Horse Canyon confluence.
- A strong relationship exists between rising alluvial groundwater levels and the substantial channel and floodplain aggradation that occurred in the 80-m subreach upstream of transect P2 between 2007 and 2014. The extent of upstream aggradation is probably crucial, as floodplain width through this subreach is constrained within the incised flood channel form. Hence, in this system, "longitudinal" groundwater storage can be an important substitute for the alluvial storage capacity of broad floodplains.
- Elevated surface flows are common during most monsoon seasons (July–September), and frequently overtop adjacent floodplain surfaces. The rate and extent of groundwater declines following these events correspond strongly to floodplain substrate composition and duration of surface flow. Fine substrate materials retain groundwater longer, enhancing local ecosystem resiliency to extended drought periods.
- Because coarse floodplain substrate limits alluvial groundwater storage both temporally and spatially, vegetation in such areas is constrained to sparse populations of species adapted to more xeric conditions. Little fine sediment is captured during overbank flows, and groundwater drains rapidly after such events. As a consequence, establishment of additional herbaceous or riparian species rarely occurs in these areas under "natural" conditions.

Recommendations

The semi-arid and highly variable climate of the southwestern U.S. makes restoring true resiliency and function in degraded riparian and wetland areas an effort that can take many years or even decades. To be most effective, monitoring should also continue over the long term. Hydrologic data collection at the sites described in this report continues. However, aging instrumentation began to reach the end of its expected life span in late 2013. Three water level transducers that failed in 2013 and 2014 were replaced, but funding for additional replacements is uncertain. Site visits, limited by volunteer capacity, have not occurred since mid-2014. The following list of recommendations addresses the importance of long-term monitoring in hydrologic restoration, the effect of data limitations on more detailed interpretation of results, and existing installation and instrumentation constraints.

- Continue data collection!
- To reduce costs in data collection and management, replace only two of the three recording transducers at each monitoring transect as failure occurs. Floodplain installations now provide the most useful data relative to evaluating restoration progress.
- Install by hand augering at least one 1 ½-inch PVC monitoring well, with a long screened interval, at the downstream face of an existing floodplain piezometer. Secure the PVC well to the existing piezometer with metal straps for stability and protection during major floods. The longer screen and coarser mesh of the observation well will help preclude clogging and slow recharge over time.
- Establish, survey, and instrument at least one monitoring transect in the transition reach between P2 and Horse Canyon, in order to capture groundwater data relevant to documenting downstream effects of increasing extent and duration of surface flows during dry periods.
- Install at least one recording stage gage within the reach ending at transect P3, to record duration and magnitude of surface flows.
- Provide for large-scale assessment by repeat satellite imagery. Other researchers working at the Pitchfork have developed reliable and relatively inexpensive methods to rapidly analyze continuous imagery series to evaluate wetness trends over time. On-site hydrologic data can be used to cross-validate results.
- Perform repeat geomorphic surveys at more frequent and regular intervals. Ideally, collect coarse-scale vegetation data (i.e., map vegetation type and elevation) during each survey. A simple method provides robust data for evaluating change in vegetation cover relative to changing channel and floodplain morphology and groundwater levels.
- Add repeat photo points at each monitoring transect; collect photos facing across the channel as well as up- and downstream.

References

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Appendices

Appendix 1. Piezometer and instrumentation details.

Piezometer	Total well depth (m)	Ground surface elevation (arbitrary datum, m)	Top of casing elevation (m)	Transducer depth (BTOC; m)	Transducer date placed	TOC coordinates (UTM NAD83, m)
P1a	4.35	310.71	310.98	4.36	03/23/07	3591591 N, 747738 E
P1b	4.65	308.74	309.42	4.62	03/23/07	3591584 N, 747733 E
P1c	1.86	308.48	308.58	none	--	3591575 N, 747728 E
P1d	2.20	309.20	309.60	2.16	03/23/07	3591570 N, 747724 E
P2a	4.27	303.35	303.85	4.21	03/23/07	3591181 N, 747940 E
P2b	4.39	302.18	302.74	3.81	03/23/07	3591179 N, 747931 E
P2c	5.19	302.23	302.86	4.80	03/23/07	3591175 N, 747920 E
P3a	3.45	303.45	304.05	3.45	03/23/07	3590417 N, 748520 E
P3b	3.68	303.36	304.05	3.43	03/31/07	3590414 N, 748509 E
P3c	4.33	304.89	305.50	3.50	03/31/07	3590408 N, 748485 E
Barologger					03/23/07	

All northing and easting coordinates in UTM, NAD83.

Appendix 2. Monitoring reach photo point locations.

Photo point no.	Northing (m)	Easting (m)
1	3587760	750044
2	3591084	747953
3	3590915	747996
4	3591253	747922
5	3590827	747981
6	3590739	748011
7	3590459	748567
11	3591219	747915
12	3591127	747940
16	3590105	748618

All northing and easting coordinates in UTM, NAD83.