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Meadow Restoration Increases Baseflow and Groundwater Storage in the Sierra Nevada Mountains of California

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Research Impact Statement: A meadow restored at the start of California's record-setting drought added at least five times more flow to the stream after restoration than before restoration, despite increased drought conditions.

ABSTRACT: In mountains of the western United States, channel incision has drawn down the water table across thousands of square kilometers of meadow floodplain. Here climate change is resulting in earlier melt and reduced snowpack and water resource managers are responding by investing in meadow restoration to increase springtime storage and summer flows. The record-setting California drought (2012–2015) provided an opportunity to evaluate this strategy under the warmer and drier conditions expected to impact mountain water supplies. In 2012, 0.1 km^2 of meadow floodplain was reconnected by filling an incised channel through Indian Valley in the central Sierra Nevada Mountains of California. Despite sustained drought conditions after restoration, summer baseflow from the meadow increased 5–12 times. Before restoration, the total summer outflow from the meadow was 5% more than the total summer inflow. After restoration, total summer outflow from the meadow was between 35% and 95% more than total summer inflow. In the worst year of the drought (2015), when inflow to the meadow ceased for at least one month, summer baseflow was at least five times greater than before restoration. Groundwater levels also rose at four out of five sites near the stream channel. Filling the incised channel and reconnecting the meadow floodplain increased water availability and streamflow, despite unprecedented drought conditions.

(KEYWORDS: meadows; floodplains; water supply; environmental impacts; restoration; climate variability/change; Sierra Nevada.)

INTRODUCTION

In the mountain headwaters of the western United States (U.S.), meadows store snowmelt and maintain shallow groundwater throughout the year in a climate with little summer rainfall. As a result, mountain meadows are highly productive, biologically diverse, and for centuries they have been among the most valued and most heavily impacted mountain environments (Wood 1975; Ratliff 1985; Anderson and Moratto 1996; Kinney 1996; Peet 2000). Many meadows are natural floodplains, and like floodplains worldwide, they have been degraded by erosion and channel incision, resulting in widespread soil loss, reduced water availability, and decreases in productivity and biodiversity (Simon and Darby 1999; Tockner and Stanford 2002; Valentin et al. 2005; Krause et al. 2011; Montgomery 2012). Before channels incised, overbank flows during snowmelt would raise groundwater levels to near the meadow surface (Kattelmann and Embury 1996; Dull 1999), and this

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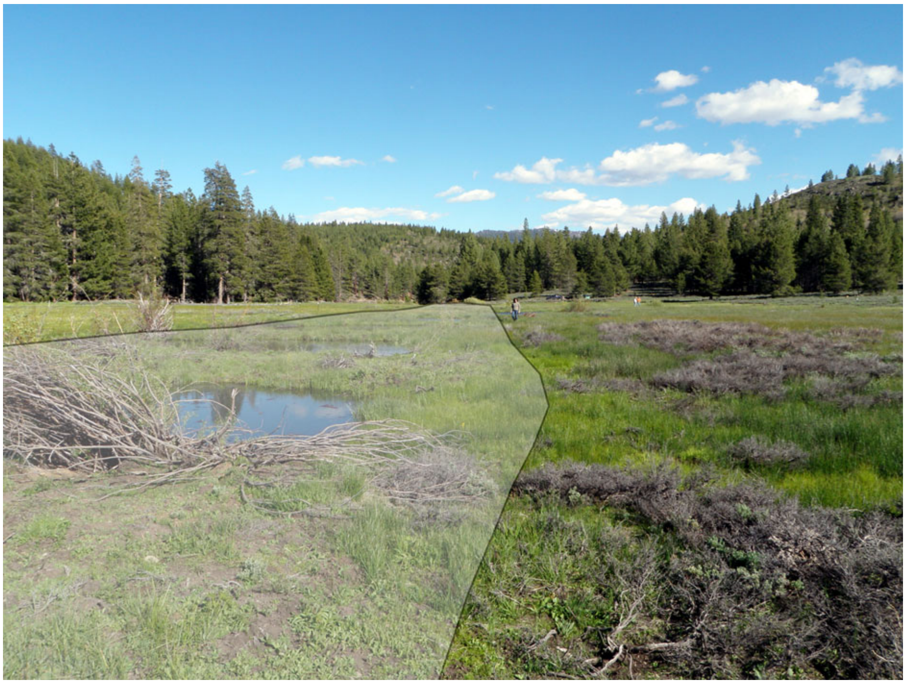

FIGURE 1. The incised channel (shaded at left) was filled using the plug and pond method in this meadow north of Lake Tahoe. Before restoration, well-drained banks supported sagebrush (shrub skeletons at right). Overbank flooding is now common; the summer water table is near the meadow surface and wet meadow vegetation is replacing sagebrush.

temporary storage was a source of baseflow during the summer and fall (Klein et al. 2007; Loheide and Gorelick 2007; Hammersmark et al. 2008; Loheide et al. 2009). Climate change is resulting in earlier melt and reduced snowpack throughout the western U.S. (Stewart et al. 2005) and water resource managers have asked whether efforts to reconnect meadow floodplains can compensate for expected shifts in snowmelt timing (CA Dept. Water Res. 2013; Upper Gunnison River Water Conservancy District 2016).

Various methods have been used to raise the bed elevation of incised channels through mountain meadows, including filling an incised channel with earth, either entirely or in sections (termed plug and pond, Figure 1), constructing check dams or brush dams, and encouraging beaver dams (NRCS, USDA 2003; Pollock et al. 2014). Throughout the western U.S., state, federal, and private sources are investing millions of dollars annually to repair incision and reconnect meadow floodplains.

In California, the state is changing water policies to invest more in meadow restoration. In 2016, the legislature identified mountain meadows as components of the state's water infrastructure, with repair costs "eligible for the same forms of financing as other water collection and treatment infrastructure" (CA Legis. Assemb. 2016). Meadow restoration is also a priority for funding under recent water bond measures and is included in the *California Climate Adaptation Strategy* as a response to earlier snowmelt (CA Legis. Assemb. 2014, 2018; CA Nat. Res. Agency 2018). Most of this funding anticipates that restoration will increase groundwater storage and summer streamflow, while providing habitat, recreation, and other benefits (USDA Forest Service 2011, CA Legis. Assemb. 2016).

One empirical (Tague et al. 2008) and three simulation studies (Hammersmark et al. 2008; Essaid and Hill 2014; Ohara et al. 2014) quantify the effect of meadow restoration on streamflow. All are from the Sierra Nevada Mountains. The effect of meadow restoration on streamflow is a balance between increased groundwater recharge, due to more frequent and extensive flooding, and increased evapotranspiration, due to shallower groundwater (Hammersmark et al. 2008; Loheide et al. 2009; Ohara et al. 2014). In three studies, restoration increased summer streamflow by expanding overbank flooding and increasing seasonal water storage within the meadow (Hammersmark et al. 2008; Tague et al. 2008; Ohara et al. 2014). In contrast, Essaid and Hill (2014) reported a slight decrease in summer flow due to increased evaporation in a steep-sided, thin meadow, where overbank flooding was unchanged between the flood-prone and incised scenarios. Studies of incised, formerly intermittent streams in the

Great Basin also report that check dams increased overbank flooding, raised groundwater levels, and led to perennial flow (Heede 1979; Swanson et al. 1987).

The record-setting California drought (2012–2015) enabled us to test if filling an incised meadow channel would raise groundwater levels and increase summer baseflows during a warm, multiyear drought. Mountain water supplies are most stressed under these conditions and climate change is expected to increase the frequency, magnitude, and duration of warm, prolonged droughts (Barnett et al. 2008; Dai 2011).

METHODS

Study Site

Indian Valley (39.591°, −119.874°) is a 62 ha meadow located at an altitude of 2,400 m on the Sierra Nevada Crest, 40 km south of Lake Tahoe (Figure 2). Deer Creek is a perennial tributary to the Mokelumne River, which flows west to join the San Joaquin River in the San Francisco Bay Delta. The north side of Indian Valley contains intermittent streams that were once tributary to Deer Creek. However, a low berm and ditch constructed before 1900 divert these streams from above the meadow, across the watershed divide so they now flow eastward into Nevada. The study area is the reach of Deer Creek through the west side of Indian Valley between the upper and lower stream gauges (Figure 2). Between mid-June and October, Deer Creek contains the only measurable surface flows in Indian Valley. Above Indian Valley, the Deer Creek watershed is 570 ha, with thin, coarse-grained, and easily eroded soils derived from Miocene andesite lahars. The elevation of the outlet of Indian Valley is set by alluvium overlying granodiorite bedrock. Below Indian Valley, most bedrock in the Deer Creek and Mokelumne River canyons is granitic.

Degradation and Restoration

As with many meadows in the Sierra Nevada, Indian Valley was heavily grazed by livestock beginning in the mid-1800s. In the early 1900s, willows were removed and portions of the valley were tilled and seeded (Chuck Loffland, El Dorado National Forest Wildlife Biologist, February 2, 2017, personal communication). The earliest photographs available, from 1950, show an incised Deer Creek channel and widespread gully erosion. Swales draining into Deer Creek were rapidly eroding upslope from unstable banks along the incised channel. By 1990, these swales had deepened into gullies that were 1.5 m deep and 500 m long and stretched from the banks of Deer Creek to bedrock at the edge of the meadow. Between 1990 and 2012, these gullies did not grow in length, but appeared to widen and deepen. Soil mottling and thick organic layers indicate the presence of a higher water table in the past, and a dewatered zone along the channel edge (visible as sagebrush in the 1950 photographs) is consistent with a degraded channel and a meadow surface that was once a regularly inundated floodplain.

In 2012, the Plumas Corporation and Eldorado National Forest used the plug and pond technique to raise the base level of the incised channel of Deer Creek through the study reach (Figure 2). Alluvium excavated from borrow areas along the channel bed and banks was used to plug sections of the incised channel to match the meadow elevation. Once groundwater rose to near the meadow surface, the borrow areas in the plugged channel filled with water and became ponds. Each plug was sloped down-valley to match the elevation of the pond downstream. As a result, the surface elevation of the plugged channel now drops in a series of slopes between ponds. Vegetation salvaged during excavation was planted to stabilize plugs, and where possible, the water was routed away from the ponds and plugs in the incised channel and into abandoned remnant channels on the meadow floodplain.

Data Collection

Stream Discharge and Meadow Contribution. In 2012, we installed logging pressure transducers (Solinst Levelogger Edge; Solinst Canada Ltd., Georgetown, ON, Canada) to measure stream stage and temperature at 15-min intervals above and below the project area, approximately 1.3 km apart and approximately 200 m from channel modifications caused by restoration (Figure 2). Barometric pressure was measured at the upper gauging station (Solinst Barologger) and used to compensate for atmospheric pressure changes. The loggers were protected by housings made of galvanized pipe drilled to allow water to enter and rigidly attached to vertical rock faces at a level that was continually submerged. During winter, Deer Creek periodically froze, and we removed data when stream temperatures fell below 1°C to avoid freezing errors.

Direct discharge measurements were only possible during summer, after spring flows had receded (approximately July–October) because snow prevented access during other seasons. As a result, the measured stage–discharge relation (rating curve) only

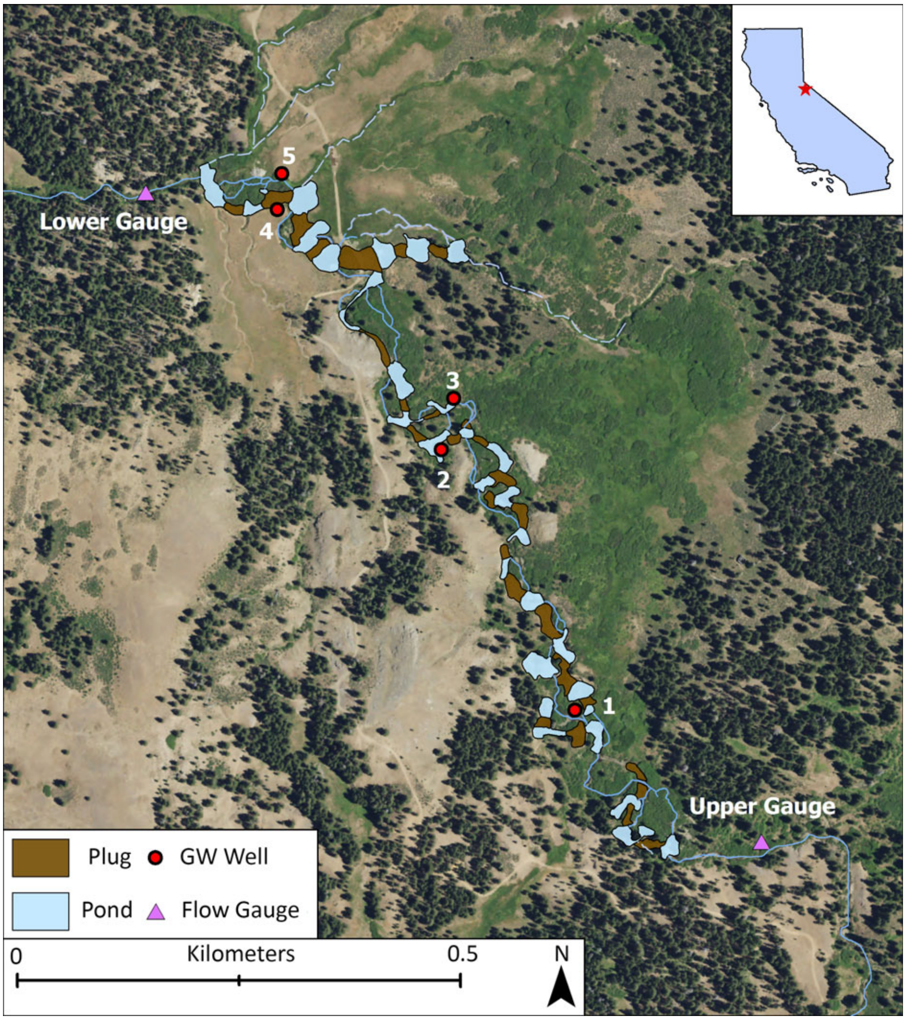

FIGURE 2. The plug and pond method was used to fill the incised channel through Indian Valley and reconnect Deer Creek with the meadow floodplain. To create 0.8 ha of plugs, alluvium was borrowed from 1.4 ha within the meadow floodplain. As the water table rose, the borrow areas filled with water and formed ponds. Flow is from the Upper Gauge to the Lower Gauge. Data from the El Dorado National Forest.

covers the range of flows below 0.03 cubic meters per second. To extrapolate the rating curve beyond the measured range of discharges, we surveyed three cross sections and a longitudinal profile at each gauge and computed a rating curve using the one-dimensional modeling program HEC-RAS (USACE 2008). This approach is similar to using the slope-area method to estimate flows for a range of stream stages when direct observation is impossible (Chow 1959).

In the winter of 2014/2015, a flood buried the upstream gauging station in 50 cm of sediment and destroyed the gauging site. As a result, continuous gauging is only available for 2012–2014 at the upstream site and 2012–2016 at the downstream site. In 2015, two summer discharge measurements were taken at the upper site before the stream inflow dried completely in late-July. A time lapse camera installed at the north end of the project took pictures every 15 min throughout the year. We used these photographs to verify unusual flow events like brief summer floods and periods with no surface flow.

We will call the gain in flow between the two gauges the meadow contribution, and it is simply the difference between the meadow outflow and inflow. The meadow contribution computed over a time period is the difference between total outflow volume and total inflow volume over the period. During summer baseflow conditions, no measurable surface flow entered Deer Creek between the gauges and the meadow contribution was entirely groundwater-derived. The baseflow period is the focus of this study (June through September). During spring snowmelt and brief summer thunderstorms, the meadow contribution included overland flow and flow from numerous short tributaries within the meadow reach. During thunderstorms, the meadow contribution swung briefly from negative to positive, as the flow peaked first at the upstream gauge and later at the downstream gauge. We removed these transient peaks by eliminating flows above the 99.9th percentile from analyses of meadow contribution. Sensitivity analyses showed that treatment of storm peaks did not change results.

Groundwater Elevation. The Eldorado National Forest and Alpine Watershed Group installed five groundwater wells in 2010 that were read by volunteers approximately monthly through the summer seasons of 2010–2015 (Figure 2).

Snow Water Equivalent. During this study, California experienced the worst drought on record, accompanied by unusually warm temperatures, which resulted in record low water storage in the spring snowpack during 2014 and 2015 (Belmecheri et al. 2016). In order to compare late-spring snowpack conditions across years, we use the May 1 snow water equivalent measured at the Carson Pass SNOWTEL station, approximately 17 km northwest of Indian Valley and 100 m higher in elevation.

RESULTS

Streamflow

Figure 3 shows the hydrographs for the upper and lower gauge locations in 2013. The hydrographs for 2013 shows a pattern that was consistent across years before and after restoration. During spring snowmelt, stream discharge into the meadow exceeded discharge out of the meadow. After mid-June, the reverse was true and outflow from the meadow exceeded inflow, except during summer storms. Outflow remained above inflow until freezing water temperatures interrupted measurements in October or November. Outflow and inflow hydrographs crossed between June 9 and June 24 each season, at which point, the meadow reach became a net source of streamflow.

The weekly meadow contribution was greater in 2013 and 2014 (after restoration) than in 2012 (before restoration) for every week, except one (Figure 4). Figure 4 also shows that the weekly meadow contribution increased from 2012 to 2013 to 2014 (Wilcoxon signed-rank test with Bonferroni correction, $p < 0.01$). A sensitivity analysis varying the end date between August 15 and October 31 indicated that the increase in meadow contribution from 2012 to 2014 did not depend on our choice of dates.

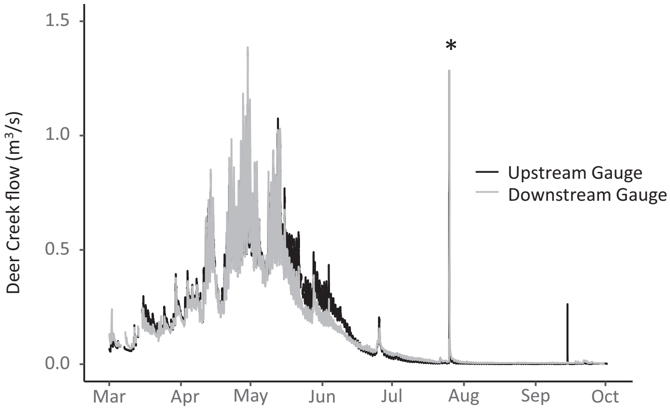

FIGURE 3. Hydrographs for 2013. Between May 16 and June 15, inflow to the meadow (black) exceeded outflow (gray). After June 15, outflow exceeded inflow. A brief, intense flood on July 26 (*) peaked at 4.3 m^3/s at the downstream gauge and 2.8 m^3/s at the upstream gauge. These peaks were removed in further analyses.

In 2015, we could not calculate the meadow contribution directly because the upper gauge was buried in sediment and destroyed. However, we observed the inflow to Indian Valley was dry on July 24, August 21, and August 24, 2015. During this period, there were no storms, so we presume that the inflow remained dry between our observations. With no inflow, the meadow contribution would have equaled the meadow outflow between July 24 and August 24. Thus calculated, the weekly meadow contribution in 2015 was greater than in previous years for the period, but with few data, this is not significant (Figure 4).

To calculate summer totals, we use the period between June 15 and September 1. June 15 was the average crossover date, when baseflow became dominant and it is likely that construction of the ponds and plugs altered flows during September 2012.

During the summer before restoration (2012), the total meadow contribution was 5% of the total summer meadow inflow volume (Table 1). During the summers following restoration (2013 and 2014), the meadow contribution was 35% and 95% of the total summer inflow (Table 1). In 2015, the meadow contribution between July 24 and August 24 (the 31 days of available data) totaled 35,000 m^3. This was five times the total summer meadow contribution in 2012 (78 days). 2015 was the only year with a prolonged period of zero summer inflow and the year with the lowest May 1 snow water equivalent (Table 1).

During May and early June of 2013 and 2014, flows into the meadow exceeded flows out of the meadow; the meadow contribution was negative. Between May 10, the last date of clear storm influence, and the crossover date when the meadow contribution became positive (Table 1, Figure 3), the total flow lost to the meadow was 131,000 m^3 in 2013 and 29,000 m^3 in 2014. The meadow contribution was also negative in June 2012; however, we were unable to

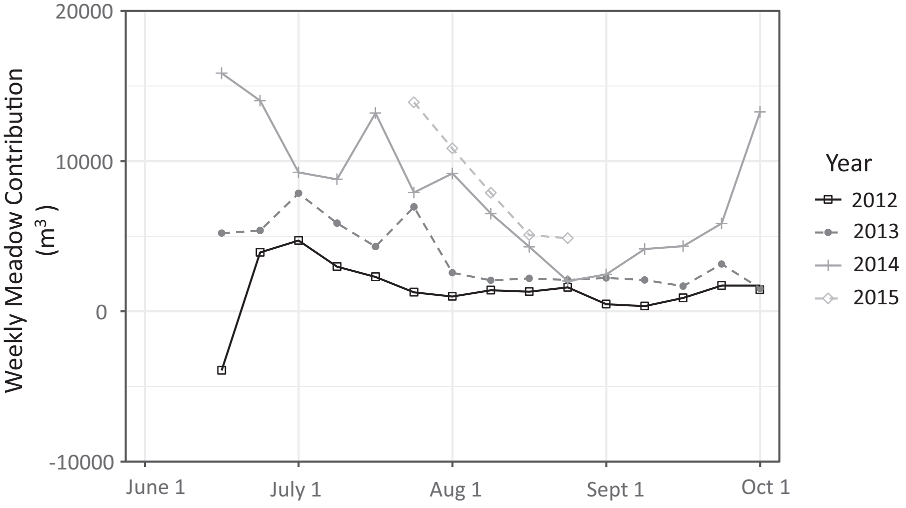

FIGURE 4. The weekly meadow contribution (m^3) is the difference between cumulative outflow and cumulative inflow for one week. Values after restoration (2013–2015) exceeded values before restoration for 14 out of 15 weeks during the low-flow period.

TABLE 1. Flow in and out of Indian Valley and the difference (meadow contribution) for June 15 through September 1.

Year	Snow water equivalent (cm on May 1)	Total summer inflow (×1,000 m^3)	Total summer outflow (×1,000 m^3)	Meadow contribution (×1,000 m^3)	Meadow contribution/ inflow	Crossover date
2012	31	136	142	7	5%	June 24
2013	24	140	189	49	35%	June 17
2014	28	101	198	96	95%	June 9
2015	0	No data	204	>35[1]	No inflow data	No inflow data
2016	61	No data	368	No inflow data	No inflow data	No inflow data

Notes: The crossover date is when outflow first exceeds inflow and the meadow becomes a source of streamflow. May 1 snow water equivalent is included to provide context for wet and dry years.

[1] In 2015, there are only meadow contribution data for July 24–August 24, when the meadow inflow was dry.

estimate the total flow lost to the meadow in 2012 because of missing data in May.

Annual maximum flows occurred during brief summer thunderstorms (Figure 3). The largest storm occurred on July 26, 2013, when a flood deposited approximately 200 m^3 of sediment within the uppermost pond. This sediment originated above the project. At the upper gauge, flow increased from <0.1 to 2.8 m^3/s in less than one hour and receded back to pre-storm levels in less than six hours. At the downstream gauge, the peak flow was delayed one hour and the maximum measured discharge was 4.3 m^3/s. The flood peaks were too brief to be estimated by 15-min sampling, so these measurements were likely less than actual peak flows. We corroborated the gauge qualitatively with time-lapse photos that showed a short period of flooding.

Groundwater

After restoration, the summer water table elevations rose significantly for Wells 1–4; there was no change at Well 5 (Figure 5, analysis of covariance, $F > 32$, $p < 0.001$). The seasonal patterns (slopes in Figure 5) were similar before and after restoration. Table 2 summarizes the rise at each well and the distance between the well and the channel. It is not clear why Well 5 was different from the other four wells. There is a weak and nonsignificant correlation between the distance from the channel and groundwater rise ($R^2 = 0.3$). Well 5 was the furthest well from the channel (23 m vs. 14 m for Well 4); however, the prerestoration water table was lower at Wells 2–4 than at Well 5 (Table 2).

DISCUSSION

The meadow contribution to summer outflow from Indian Valley increased substantially after restoration (Table 1). After the incised channel was filled, high flows spread out across a larger area of meadow

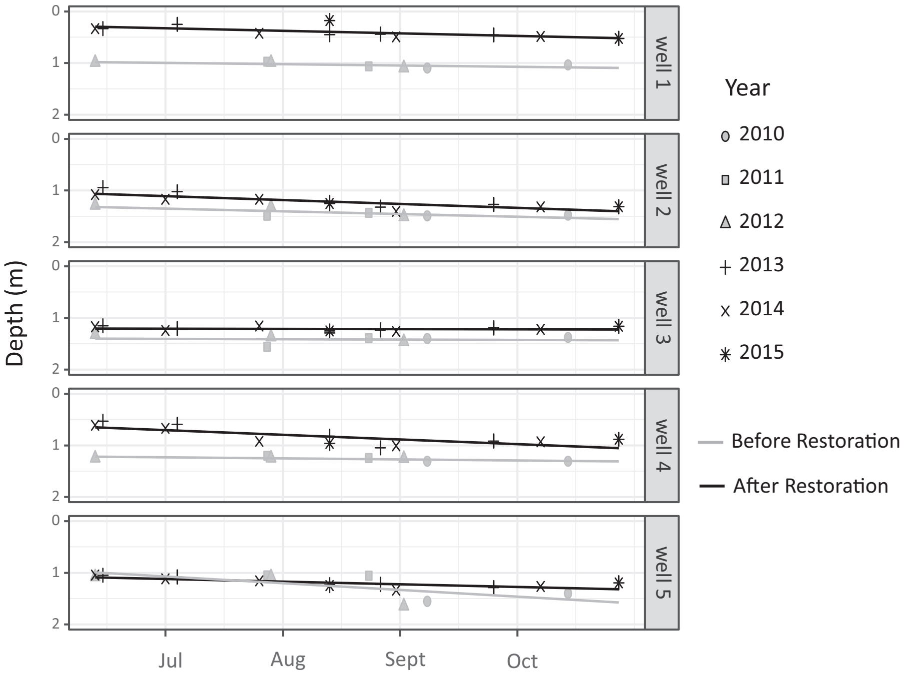

FIGURE 5. Groundwater elevations after restoration (black) were higher than before restoration (gray) for Wells 1–4 (ANCOVA, $F > 32$, $p < 0.001$). Regression lines combine data for the years before restoration (2010–2012, filled symbols, gray lines) and after restoration (2013–2015, black lines). ANCOVA, analysis of covariance.

TABLE 2. Water table at each well before and after restoration and the average water table rise after restoration.

	Water table depth before (m)		Water table depth after (m)			
Well #	**Mean**	**SD**	**Mean**	**SD**	**Water table rise (m)**	**Distance from channel (m)**
1	1.0	0.05	0.4	0.11	0.64	9
2	1.4	0.13	1.2	0.14	0.17	12
3	1.4	0.13	1.2	0.05	0.16	8
4	1.3	0.04	0.8	0.18	0.44	14
5	1.3	0.26	1.3	0.32	0.00	23

and summer groundwater elevations rose at four out of five sites. Groundwater comparisons are based on three summers of pre- and postrestoration measurements. Flow comparisons are based on one summer of prerestoration flow measurements (2012) and three summers of postrestoration flow measurements (2013–2015). To attribute increased flow and shallower groundwater to restoration rather than annual variation, we must demonstrate that the years after restoration were no wetter than the years before restoration.

In fact, the years after restoration were drier than before restoration. California experienced a record drought between 2012 and 2015 and snowpack and meadow inflow records indicate drier weather in Indian Valley after restoration. Compared to 2012, spring snowpack was reduced in 2013 and 2014 (23% and 10% lower), and in 2015, there was no snow present on May 1 (Table 1). In 2010 and 2011, the May 1 snowpack was 16% and 65% more than in 2012. Summer inflows were not affected by the project and also indicate similar or drier conditions in the years following restoration. Summer inflows in 2012 were similar to summer inflows in 2013 (3% increase in 2013) and somewhat reduced in 2014 (25%). In addition, manual discharge measurements confirm that the gauges in 2012 were not biased (e.g., by movement of the gauge).

We did not have continuous inflow data for 2015; however, 2015 was the only summer in our record with a prolonged period of zero inflow, from July 24 to August 24. With a prolonged dry period and zero snow on May 1, it is likely that 2015 had the lowest summer inflow of any year during the study period, yet summer outflows were slightly higher than in 2013 and 2014 and more than 40% higher than before restoration (Table 1). In addition, between July 24 and August 24, 2015, when there was no inflow and we could therefore calculate meadow contributions, 2015 had the highest weekly meadow contributions of any year (Figure 4). Thus, it appears that the meadow contribution may have been greatest during 2015, the worst year of the drought.

Others have reported that groundwater levels and outflows have taken multiple years to recover following meadow restoration (Jim Wilcox, Plumas Corporation, Craig Oehrli, U.S. Department of Agriculture Forest Service, October 22, 2015, personal communication). We observed stable summer groundwater levels by the first year after restoration, so it was surprising to us that the summer meadow contributions increased significantly from 2012 through 2014 and appears to increase further in 2015 (Figure 4). However, our groundwater wells were all near the channel (Figure 2, Table 2) so we could not have detected effects farther from the channel and cannot rule out multiyear groundwater changes after restoration.

The lowered water table caused by channel incision is analogous to the depression cone due to groundwater pumping. The greatest drawdown is near the incised channel (Essaid and Hill 2014) which results in a characteristic vegetation signature. Upland vegetation is found near the channel, where the drawdown is greatest, while areas farther from the channel continue to support wet meadow vegetation (Loheide and Gorelick 2007). In the Eastern Sierra Nevada, this dewatering signature can be striking: a band of sagebrush rims incised channel banks and wet meadow vegetation is limited to areas farther from the channel. Beneath the sagebrush canopy, remnant perennial wetland species (e.g., *Carex*, *Juncus*) are often present in low abundance. Where restoration efforts have raised the water table, wetland vegetation has resumed dominance and stabilized soils without seeding or other interventions (Figure 1). We also observed upland vegetation on well-drained channel banks before restoration and rapid colonization by wetland species after the water table rose.

We focused on the summer period because this is when water is most valuable and the effect of restoration on summer baseflow was clear. The effect on total annual flow was less clear and differed between 2013 and 2014. During 2013, the volume Deer Creek lost to the meadow during spring was nearly three times the volume the creek gained during summer. In 2014, the reverse was true; the volume gained by Deer Creek during summer was three times the volume lost during spring. Hammersmark et al. (2008) found that restoration slightly reduced the total annual outflow (by increasing water availability and evapotranspiration), but the volume was not measurable.

One way to place a value on the water lost and gained by the meadow during different seasons is to consider the nature of its use downstream. In springtime, the Sierra Nevada snowpack is by far California's largest surface reservoir (Dettinger and Anderson 2015). Climate change is resulting in earlier melt and reduced snowpack throughout the western U.S. (Stewart et al. 2005) and water resource managers have asked whether the delayed release of streamflow resulting from meadow restoration can benefit water supplies and hydropower operations and compensate for these shifts in snowmelt timing (CA Dept. Water Res. 2013). Approximately 30 km downstream of Indian Valley, Salt Springs Dam diverts the Mokelumne River for hydropower generation. In May and June, flow that exceeds the diversion capacity has been released in 9 out 15 years between 2000 and 2015 (California Data Exchange Center, Station SLS). At this time of year, additional water from meadow restoration would presumably have little value. Conversely, water added to the system when the reservoir has storage capacity (after July in regular years and at all times during drought years) would presumably add value. After July, the meadow contribution in Indian Valley is positive. We only have postrestoration data during drought years, when Salt Springs Reservoir did not release. If the pattern holds for nondrought years, as others have shown, and if we assume that the value of water when the reservoir is releasing is zero, then the water supply value of restoration would equal the value of the meadow contribution volume, once Salt Springs Reservoir stops releasing.

SUMMARY

In the Sierra Nevada, the water table has been drawn down by channel incision across thousands of square kilometers of meadow (USDA Forest Service 2015). In Indian Valley, 0.1 km^2 of floodplain area was hydrologically reconnected by filling the incised channel. This occurred in 2012, at the beginning of California's recent drought. Despite the drought, baseflow volumes increased after restoration and groundwater levels rose. A sponge is a popular analogy for floodplains and meadows that "soak up" spring flows and augment streamflows during summer and fall (Rodriguez et al. 2017). This analogy works for Indian Valley — the meadow contribution was negative during springtime and positive during the summer and fall. After restoration, the summer baseflow volumes contributed by the meadow increased 5–12 times over prerestoration volumes. After restoration, the meadow contribution added between 35% (2013) and 95% (2014) to the total summer flow entering the meadow, nearly doubling streamflow during the summer of 2014. In 2015, when inflow ceased for at least one month, outflow was continuous throughout the summer and total summer baseflow was at least five times greater than before restoration. Groundwater levels also rose at four out of five sites near the stream channel.

This study is part of a growing body of work indicating that meadow restoration can increase streamflow and groundwater retention in headwater regions. Our conclusions support recent initiatives to increase investment in meadow restoration as a strategy to improve water management and climate resiliency in mountains of the western U.S.

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