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Conceptual models for surface water and groundwater interactions at pond and plug restored meadows

K. Rodriguez, S. Swanson, and A. McMahon

Abstract: The pond and plug meadow restoration method, used for incised meadows in the Sierra Nevada Range, takes available alluvium on site to dam the incised channel in several places. Groundwater storage gained from restoration may alter flow paths and surface water availability. Water flowing through the meadow is elevated, usually to an alternate channel, and slowed by floodplain spreading, meanders, and vegetation roughness. Each dam, or plug, creates a pond, filled as the water table rises closer to the meadow surface. Expanded riparian vegetation and slowed water movement increase evapotranspiration (ET) following restoration. Landsat derived Normalized Difference Vegetation Index (NDVI) increased by 0.07 (p <0.001) on 30 of 31 meadows. Conceptually a meadow may act as (1) a sponge, storing abundant water from snowmelt or precipitation and releasing water in dry periods; (2) a valve, regulating water outflow from springs recharging the meadow, and/or (3) a drain, allowing water from the meadow to percolate into a regional aquifer. Areas in eight northern California meadows were classified into one or more of these conceptual models using ET, summer pond and groundwater elevations, stream gauges, and climate data. Evaporation from open pond water was 20% to 80% of their summer decline (–0.11 to 1.78 m [–0.36 to 5.84 ft]) and 1% to 7% of total meadow ET. Meadow ET estimates ranged from 0.32 to 0.40 m (1.05 to 1.31 ft). Water from springs captured by historic channel incision can be redirected from discharge to meadow restoration and ET. This study was conducted in a dry period and the data reflect effects of below average precipitation.

Key words: evapotranspiration—hydrology—meadow restoration—pond and plug

Headwater montane meadows are an important source of water for California, and thus it is crucial to understand the interactions between surface water and groundwater. Winter (2007) provides description of various interconnections between surface and groundwater. Because the rates of water flow, the topography, and vegetation vary among regions, Prichard et al. (2003) and Dickard et al. (2015) provide extensive references and emphasize the importance of understanding local potential (soil-landform, hydrology, and vegetation) to assess riparian functions.

Herbaceous meadows occur where saturated anaerobic soils preclude woody upland vegetation. Many meadows are floodplains that dissipate flood energy and store water. Stream degradation leads to incised channels and reduced groundwater storage. An incised stream lowers the water table, alters stream flow, and decreases meadow functionality (Hill 1990, 2011; Prichard et al. 1998; Loheide and Gorelick 2007; Loheide et al. 2009; Loheide and Booth 2011; Dickard et al. 2015). Lowered groundwater tables dehydrate riparian-wetland plants that persist only with sufficient soil water (Elmore and Beschta 1987; Heede 1979; Lowry and Loheide 2010; Hill 2011).

The pond and plug technique for meadow restoration has been successfully used in northern California for the past 25 years. These projects, developed in the early 1990s (Lindquist and Wilcox 2000), alter the hydrology and ecosystem of mountain meadows. Published studies of restored meadow hydrology tend to be single meadow case studies (Loheide and Gorelick 2005, 2007; Tague et al. 2008; Hammersmark et al. 2008; Hammersmark et al. 2009; Loheide and Booth 2011). Missing from the case study research is the effect of created ponds on surface flows. There has been little study of the hydrological interaction between ponds and restored meadows (Klein et al. 2007; Tague et al. 2008; Hammersmark et al. 2010; Essaid and Hill 2014). Pond behavior during the dry season may explain some variations in downstream baseflows late in the season, when they are most needed (NFWF 2010).

Pond and plug projects use alluvium available on site to reconnect streams to the floodplain. Material is removed from the sides of the incised channel to form plugs, or thick dams, constructed to just above terrace elevation. Plugs prevent surface water and sediment transport downstream through the gully. The stream is redirected, usually into a historic or new channel that often floods the now reconnected floodplain. This also elevates the water table surface. The ponds form in widened and/or deepened areas of the incision as groundwater rises (Hammersmark et al. 2009).

Stream access to the floodplain allows the stream channel to return to a natural pattern or sinuosity, profile or gradient, and dimension (width and depth) with an improvement in the functionality of the riparian meadow (Hammersmark et al. 2008; Tague et al. 2008; Dickard et al. 2015). Reconnection with the floodplain restores wet conditions to the meadow and promotes recruitment and expansion of riparian plants while decreasing the extent of xeric plants in the riparian zone (Elmore and Beschta 1987; Allen-Diaz 1991; Tague et al. 2005; Loheide et al. 2009; Hammersmark et al. 2009; Weisberg et al. 2012; Loheide and Booth 2011).

The expansion of wetland riparian phreatophytes increases meadow evapotranspiration (ET). Phreatophyte ET depends on climatic, radiative, and atmospheric driver

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variables (solar radiation, wind, humidity, precipitation, and temperature), vegetation composition (species and distribution), soil composition (type, thickness, capillarity, and moisture), and depth to water (Tague et al. 2005; Beamer et al. 2013). ET increases after restoration are neither spatially nor temporally constant, largely due to variations in topography, weather, and depth to groundwater (Loheide and Gorelick 2005; Hammersmark et al. 2008). A goal of restoration is expanded riparian plant communities, which is related to increases in ET. For example, Hammersmark et al. (2008) modeled ET increases from 25% to 50% in two different water years. In the Last Chance Creek watershed (Sierra Nevada Range, northern California), Loheide and Gorelick (2005) estimated ET in restored and degraded meadows using an ET mapping algorithm that uses meteorological data, vegetation data, and thermal imagery. Restored meadow estimated ET for a single day in 2004 ranged from 5 to 7 mm d^{-1} (0.2 to 0.28 in day^{-1}), almost double estimated ET for a degraded riparian area (1 to 3.5 mm d^{-1} [0.04 to 0.14 in day^{-1}]). They also found that vegetation growing on the plugs transpired less per unit area than the rest of the meadow, most likely a result of the plugs being slightly elevated above the meadow surface and farther above the water table (Loheide and Gorelick 2005).

Increased evaporation from newly created ponds adds to transpiration from the newly recruited riparian plant communities, and these phenomena cause concern to downstream water users who rely on perennial stream flow (Ponce and Lindquist 1990; Hill and Mitchell-Bruker 2010). Case study research describes how pond and plug projects affect baseflow downstream of the project (Loheide and Gorelick 2005; Tague et al. 2008; Hammersmark et al. 2008, 2009; Loheide et al. 2009; Ohara et al. 2013). Hammersmark et al. (2008) built a three-dimensional model to compare runoff and groundwater levels before and after restoration. The model indicated that restoration decreased flood peaks, increased groundwater storage, increased floodplain inundation, and decreased baseflow. Proposed explanations for decreased runoff and baseflow in the model were increased groundwater storage and increased ET (Hammersmark et al. 2008). Conversely, Ohara et al. 2013 found that baseflows increased after restoration. Their model indicated a 10% to 20% decrease in winter flood flows and a 10% to 20% increase in dry summer baseflows in comparison to prerestoration flows. Restoration changes flow regimes through slowed meadow flows, allowing for groundwater percolation and reduced sediment transport (Ohara et al. 2013).

For the Last Chance Creek watershed, Loheide and Gorelick (2007) built a hydrologic flow model of three meadow types (pristine, restored, and degraded) that incorporated vegetation. In the degraded meadow model, there is less recharge early in the water year. Recharge and baseflow peak early in the summer and drop more quickly than in the restored and pristine meadows, which dampen early season runoff peaks and where saturation persists from retained water. In the incised meadow, groundwater flow paths were primarily to the stream, compared to down valley flow paths in the restored and pristine cases. Downstream discharge during the summer and during droughts was greater in the restored and pristine meadow cases (Loheide and Gorelick 2007).

Tague et al. (2005) found similar post-restoration effects on changes in baseflow above and below the project before and after restoration. Following restoration, discharge increased in early summer (June and July) below the project and decreased later in the summer and into the fall. Decreased late summer baseflow was attributed to an increase in ET resulting from increased area of riparian vegetation (Tague et al. 2005).

The scientific community lacks a consensual explanation for changed baseflows following restoration. Furthermore, results may vary depending on site conditions and variations in weather from year to year (NFWF 2010; Loheide et al. 2010; Hill 2011). A meadow's hydrologic characteristics are strongly linked to precipitation. The seasonal pattern and variability among water years in northern California strongly influence available water. There is an interannual and intraannual variation in streamflow independent of restoration (Tague et al. 2005). The timing and speed of snowmelt are changing with changes in climate (Lowry et al. 2010). Therefore, it is important to analyze data from multiple continuous water years to look for seasonal fluxes and to extract the response to restoration from climatic trends (Tague et al. 2005; Hammersmark et al. 2008; Essaid and Hill 2014).

Several studies (Seevers and Ottmann 1994; Szilagyi et al. 1998; Szilagyi and Parlange 1999) have developed empirical relationships between ET and Normalized Difference Vegetation Index (NDVI) using infrared (NIR) and visible (VIS) parts of spectral reflectance (NDVI = [NIR – VIS] ÷ [NIR + VIS]) in water limited environments. Satellite remote sensing data provide information on environmental trends; interannual changes in NDVI can be linked to climate and environmental controls at the meadow level (Debinski et al. 2000). NDVI is also a useful tool for monitoring vegetation dynamics on a regional scale (Peters et al. 1997).

Loss of wetland plants coupled with lowered groundwater tables allows intrusion of drought tolerant upland plants (native and invasive) onto the aerobic soils of the terrace that was once the active floodplain (Loheide and Gorelick 2005; Loheide et al. 2009). Vegetation changes along stream banks often accelerate bank destabilization and erosion due to lack of stabilizing root masses (Heede 1979; Prichard et al. 1998; Dickard et al. 2015).

Three conceptual models (sponge, valve, and drain) proposed by Hill (2011, 2012) were used to compare and contrast the hydrologic interactions of restored mountain meadows. This study investigates pond-stream-groundwater interactions in restored meadows using these conceptual models. Understanding and classifying these interactions can help explain and predict postrestoration hydrological responses among restored meadows, ponds, and ground or surface water (Hill 1990, 2011). This study used eight meadows (figure 1) to understand common tendencies and site-specific variation through the use of conceptual models.

In the sponge model, alluvium in meadows stores runoff and interflow discharges to streams in water limited periods. In meadows with traits of the sponge model, upstream flood flows entering the meadow are slowed via bank storage or surface infiltration. This dampens discharge variance. Flood flows are also stored in the meadow. This storage slows the transport of water and sustains groundwater and pond elevations during dry months (Tague et al. 2008; Hill 2011), especially at the lower end of meadows, where pond elevations may remain at or above the streambed elevation during the dry season.

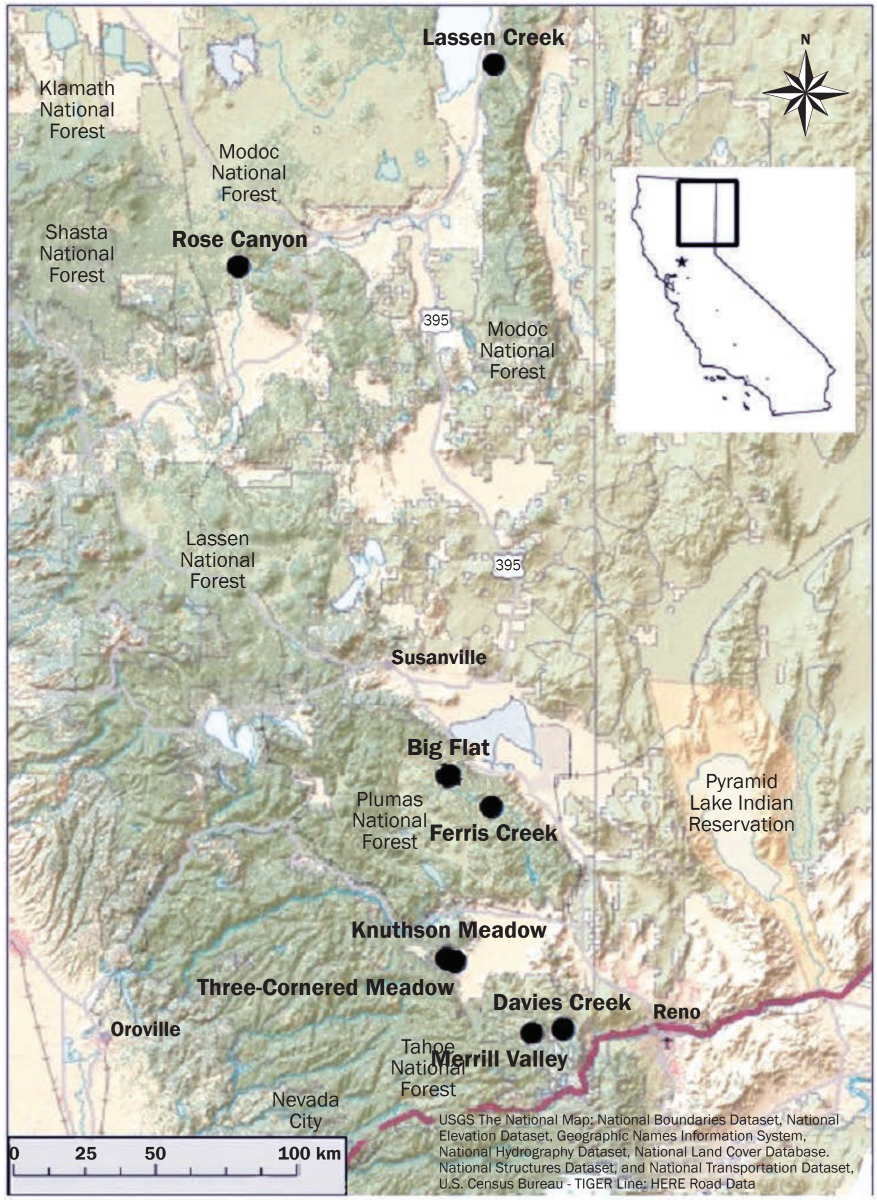
The valve model describes groundwater discharge meadows. In these meadows, groundwater discharge occurs via meadow springs, seeps, and upwelling on a small (localized to a fraction of the meadow) or large (meadow-wide) area. A localized spring may be evident in an area where pond elevations remain fairly constant in summer while ponds not supplemented by a spring lose water to seepage and ET. In a meadow-wide valve situation there may be greater stream discharge below than above the meadow (different from the sponge model where slowed transport of water through the meadow simply dampens and delays runoff events). In the dry season, saturated meadow areas, as well as pond declines less than predicted, may indicate groundwater discharge.

The drain model (groundwater recharge meadow) describes meadows where surface water and groundwater recharge deep aquifers. Streams in these meadows may experience a net loss in baseflow (Tague et al. 2005; Hill 2011) larger than predicted from ET. If ponds overlay concentrated seepage areas or bedrock fractures, these pond(s) may have lower water levels or more rapid drainage. In meadows with the drain conceptual model present, pond declines may be more than predicted by ET alone.

Study Area. Eight northern California meadows were selected in 2012 from a list of 39 pond and plug restored meadows (figure 1; table 1). Site selection was based on the meadows having at least three consecutive ponds not connected to each other or to the stream channel via surface flow. This criterion enabled the use of pond elevations as indicators of groundwater levels. At each meadow, all ponds included in the restoration project were sampled. Davies Creek is shown as an example of site design (figure 2).

The meadow climates range from mediterranean to montane. Table 1 depicts the size, setting, and history of project sites. Included in table 1 is potential groundwater storage following restoration. This is based on specific yield (S_y), the portion of saturated soil volume available for release with water table decline (lowest S_y = 0.01 to highest S_y = 0.31)—obtained using average values for each soil textural class (Johnson 1967; Loheide et al. 2005), and the dimensions of preproject gullies obtained from prerestoration surveys and practitioner estimates (Jim Wilcox, Plumas Corporation, unpublished data 2013; Rick Poore, StreamWise, unpublished data 2013; Randy Westmoreland, personal communication, 2013). Gully dimensions and S_y were multiplied by meadow area to estimate potential groundwater storage gained from restoration.

Figure 1
Map of study extent (Esri 2013).



Materials and Methods

In June of 2012, In-Situ Rugged Troll 100 (In-Situ, Fort Collins, Colorado) pressure transducer loggers were installed in selected locations (streams, meadows, and ponds) at each site. Perforated stilling wells constructed of 1.52 m (5 ft) lengths of 3.18 cm (1.25 in) diameter PVC were driven 1.3 m (4.27 ft) deep (drive point wells) into stream or pond sediments. A logger suspended 1 to 2 cm (0.39 to 0.79 in) off the bottom by steel wire recorded pressure, water depth, and temperature at one hour intervals. Near each meadow, an In-Situ BaroTroll 100 barometric pressure transducer was installed above water surfaces to account for barometric air pressure using In-Situ Baro Merge software (https://in-situ.com/support/documents/baro-merge-software/).

Loggers were placed in stream channels where possible (six of eight sites) on the downstream and upstream end of the restored meadow. In each meadow, shallow

Table 1
Basic features of each project: area, width, and gradient (Esri 2013); gully depth, restoration year, and cited damages (Jim Wilcox, Plumas Corporation, unpublished data 2013; Rick Poore, StreamWise, unpublished data 2013; Randy Westmoreland, personal communication, 2013); average annual precipitation (USGS 2012); and soil types (Soil Survey Staff 2015). Geology was determined using ArcMap layers created by the US Geological Survey from the Geologic Map of California (Jennings et al. 1977). WRCC stands for Western Regional Climate Center.

Site	Coordinates	Area (m^2)	Width (m)	Study ponds	Valley gradient (%)	Gully depth (m)	Restoration date	Cause of degradation	Watershed annual precipitation (cm)	Surface soil texture	Soil parent materials	Estimated storage gained from restoration (m^3)	WRCC station name (ID number)
Big Flat	40°9‘ 3.51” N, 120°27’ 25.17” W	177,413	276.5	7	1.37	2.76	1995, 2004	Livestock grazing, logging	68.8	Gravely-sandy loam	Alluvium, basalts	107,415	Laufman (040244)
Davies Creek	39°31' 19.84" N, 120°11' 46.42" W	18,313	105.5	5	1.64	1.07	2008	Livestock grazing, railroad grade	93.9	Silty-clay loam	Mixed rock	199	Stampede (041310)
Ferris Creek	40°4’ 27” N, 120°19’ 37” W	203,167	323.6	9	1.42	3.02	2004	Livestock grazing, channelization of stream	62.2	Silty-clay loam	Alluvium terrace	137,451	Laufman (040244)
Knuthson Meadow	39°42’ 2” N, 120°27’ 46” W	953,892	462.7	15	1.04	2.74	2001	Livestock grazing, railroad grade	62.3	Silty-clay loam	Alluvium derived from mixed	22,545	Coyote (040917)
Lassen Creek	41°50’ 27” N, 120°18’ 38” W	171,972	174.9	25	1.18	1.86	2005	Livestock grazing, irrigation ditch	68.6	Loam	Sediments weathered from volcanic rock	4,149	Cold Springs (040314)
Merrill Valley	39°31’ 47.6” N, 120°5’ 48.9” W	239,141	513.9	24	3.96	1.91	2008	Livestock grazing, railroad grade	97.5	Silty-clay loam	Alluvium derived from mixed	3,938	Stampede (041310)
Rose Canyon	41°22’ 19” N, 121° 7’56” W	135,212	292.6	11	1.88	1.88	2010	Channelization and livestock grazing	54.6	Silty-clay loam	Alluvium derived from mixed	3,859	Canby (040303)
Three-Cornered Meadow	39°42’ 9.5” N, 120°27’ 44.4” W	109,271	318.9	8	0.38	1.90	2002	Livestock grazing, stream diversion, logging	76.7	Silty-clay loam	Alluvium derived from mixed	2,649	Cold Springs (040314)

wells were installed at the upper and lower ends of the meadow and in at least one stilling well in a selected pond. Where keeping the loggers submerged was not possible, the logger was removed (2 of 43 loggers) for winter to avoid freeze damage. Hourly logger readings were averaged on a daily basis to mask diurnal fluctuations.

Field discharge was not measured due to insufficient stream flows. Instead, Manning's Equation was used to calculate discharge based on stage (Fetter 2001), channel dimensions, slope, and roughness (n). The n value for the equation was estimated using observed streambed and vegetation characteristics. For each site, upstream and downstream n values were assigned (Fetter 2001). Assumptions of rectangular channels and uniform flow were used in the calculation of discharge, causing uncertainties in discharge calculations. However, in the absence of discharge measurements, these estimates provide useful information for evaluating relative magnitudes of water budget components.

Figure 2

Aerial view of Davies Creek with logger locations (Esri 2013). DSGW = downstream groundwater. USGW = upstream groundwater.

Water level was surveyed at each study pond, stream staff, and well location using procedures in Archbald (2008). Valley distance and corresponding pond locations were calculated using a Trimble Nomad handheld computer (Trimble, Inc., Sunnyvale, California)/global positioning system (GPS) and the program SOLO Field (Tripod Data Systems, Corvallis, Oregon). Locations of ponds and other meadow features (wells and stream channel) were recorded using the Universal Transverse Mercator coordinate system (UTMs). The easting and northing coordinates were used as x and y coordinates for the Pythagorean theorem to calculate distance of features from the downstream benchmark. During elevation surveys, the area of each pond is calculated using a handheld GPS device (TDS 2007). Pond volume declines are calculated from field measurements. The volume of water lost is calculated by comparing pond area and elevation at the beginning and end of the season. The volume of water lost is calculated assuming sloping sides as:

1/3 Change in Area (Primary Visit Area – Final Visit Area) × Change in Elevation (Elevation Primary Visit – Elevation Final Visit). (1)

Annual 2011 to 2014 precipitation values from the Parameter elevation Regression on Independent Slopes Model (PRISM) were obtained for four subbasins (Little Truckee River, Last Chance Creek, Lassen Creek, and Carmen Valley). The normal precipitation value was determined based on 30 years of data (1984 through 2014), and also from PRISM. This study began in June of 2012 and was completed in October of 2014. Dry weather after 2011 made it impossible to look at meadows' response to above average water years. Instead this study focuses on meadows' response to a dry period.

To estimate average summer reference ET and pond evaporation, daily meteorological data were obtained for the summer of 2012 from the closest Western Regional Climate Center (WRCC) station to each meadow (table 1; WRCC 2013). The meteorological data were used with daily data from BaroTroll loggers to calculate reference ET (ET_o). Reference ET was calculated using area of the meadow and the program Ref-ET (Allen 2013) using the Food and Agriculture Organization of the United Nations (FAO) Pennman-preparation for the NDVI analysis; reference ET was also calculated using downscaled North American Land Data Assimilation System (NLDAS) station data (Abatzoglou 2011). To calculate daily pond evaporation (E_p), ET_o was multiplied by 1.05 (adjustment factor for surface water less than 2 m [6.56 ft] deep) (Allen et al. 1998). Daily pond evaporation was converted to a volume of water (m^3).

Using published relationships between vegetation indices and ET, we compared pre- and postproject vegetation and ET with summer (July, August, and September) NDVI from 1985 through 2011. These months were selected under the assumption that spring runoff would have subsided and meadow vegetation would be primarily utilizing groundwater. Thirty pond and plug restoration projects, restored between 1985 and 2011, were digitized in ArcGIS, including the eight sites from model analysis. Each meadow was outlined and all water was masked out. Average NDVI was calculated for the summer months (July, August, and September) from 1985 through 2011. Spatially averaged Landsat derived NDVI for each meadow was calculated with the Google Earth Cloud Computing and Environmental Monitoring Platform. This uses Landsat Thematic Mapper (TM5) at-surface reflectance (Tasumi et al. 2008), and the NLDAS precipitation data (USGS 2015).

Results and Discussion

Rose Canyon was restored most recently of the eight instrumented projects. Flows entering the meadow are flashy and infrequent, compared to downstream discharge with a more constant baseflow ranging from 0.5 to 1 $m^3\ s^{-1}$ (17.67 to 35.31 $ft^3\ sec^{-1}$) (figure 3).

Lassen Creek is the most northern and only restoration project with perennial flow. The stream runs alongside the ponds for the length of the meadow. Pond water elevations declined across dates in 2012 (figure 4); pond elevation changes were minimal (less than 0.125 m [0.41 ft]) at 17 of 19 ponds (figure 4). The other two (Pond 14 and Pond 18) declined by 0.425 and 0.65 m (1.39 and 2.13 ft). At Lassen Creek there was less pond elevation fluctuation in 2012 (figure 4) than in 2013, especially in upstream ponds, possibly due to watershed carry over from the wet winter preceding the study (table 2). The lack of pond elevation fluctuations could also be explained by the perennial stream maintaining groundwater elevation near most ponds.

Merrill Valley has the largest number of ponds and plugs. In the middle section of Merrill Valley there is no stream channel. At the upper and lower end of the meadow there is a stream channel, and generally discharge is greater downstream than upstream, an attribute of the valve model (groundwater discharges to the stream). Greater discharge below the meadow after peak flows would also indicate the sponge model, but at Merrill the downstream discharge increases before upstream discharge. Differences in pond and groundwater elevations (figure 5) indicate upwelling in the lower meadow.

The lowest meadow pond and groundwater well experienced less elevation fluctuation, potentially due to groundwater discharge. The uppermost pond lost water to groundwater and in one summer completely dried. In the midreach of the meadow pond, elevations drop below the stream bed elevation, an indication of groundwater recharge. On the upstream and downstream sides of this midmeadow groundwater recharge area there are areas of groundwater discharge, indicated by the ponds that remain above the streambed elevation.

Ferris Creek is an intermittent stream. Increased flow below the meadow (not shown) can be attributed to groundwater discharge. A spring discharges into the lower pond (Jim Wilcox, Plumas Corporation, personal communication, 2015) where there is less fluctuation than in the lower groundwater elevation (figure 6). Other ponds are above the groundwater and slowly lose water to groundwater (figure 6). At several places groundwater wells went dry. In the winter of 2012 through spring of 2013 pond elevations were stable (figure 6) due to meadow saturation. Unfortunately logger malfunction at the lower pond made it infeasible to determine if the meadow was saturated the following winter.

Davies Creek is the smallest meadow by area and number of ponds. Initially, two pond loggers and two groundwater wells were installed (figure 7). However, due to lack of water, the lower pond logger was removed. A possible explanation for the dried pond is a low permeability confining layer below the pond that does not allow groundwater discharge into the pond. The downstream and upstream discharge estimates were similar for the duration of the study. In general, there is more discharge into than out of the meadow. The upper pond elevation remains above the elevation of nearby groundwater, a possible sink away from a pond (figure 7). Comparisons of the downstream and upstream loggers indicate a relationship between stream discharge at the top and bottom of the meadow. The pond elevations in the summer of 2012 (figure 8) declined more at the lower part of the meadow (Ponds 1 through 4), than the upper meadow where there was evidence of a localized source of groundwater discharge into the upper pond (Pond 5) observed in the field and corroborated with minimal elevation changes (figure 8).

Figure 3
Rose Canyon upstream vs. downstream discharge comparison (June 24, 2012, through September 15, 2014). Lack of black or gray line indicates that the stream had no water.

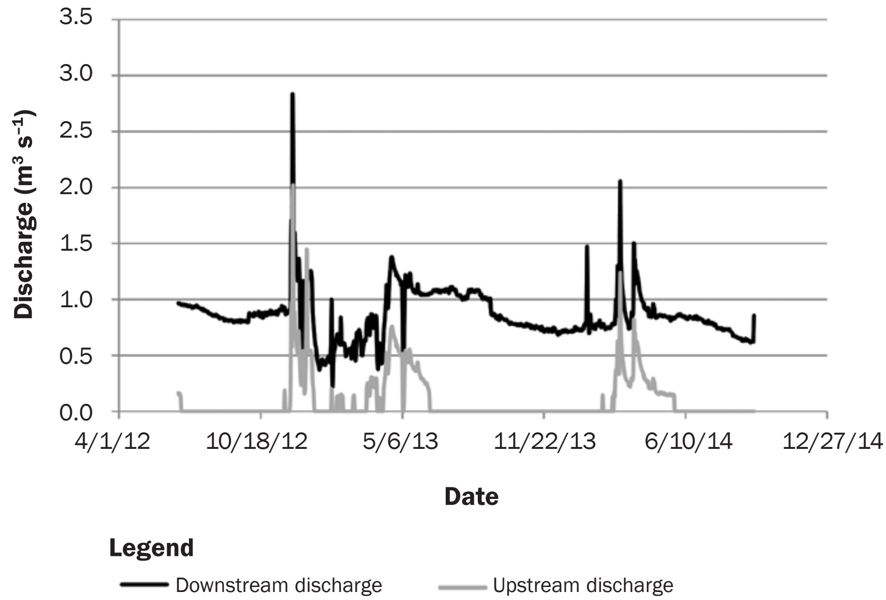


Figure 4
Lassen Creek pond elevation changes in the summer of 2012. Pond elevation and valley distance are plotted starting from the downstream benchmark, which represents an elevation and a valley distance of zero. The three lines with symbols represent a different site visit, with a symbol for each survey date. The streambed generally runs alongside ponds and not through the ponds.

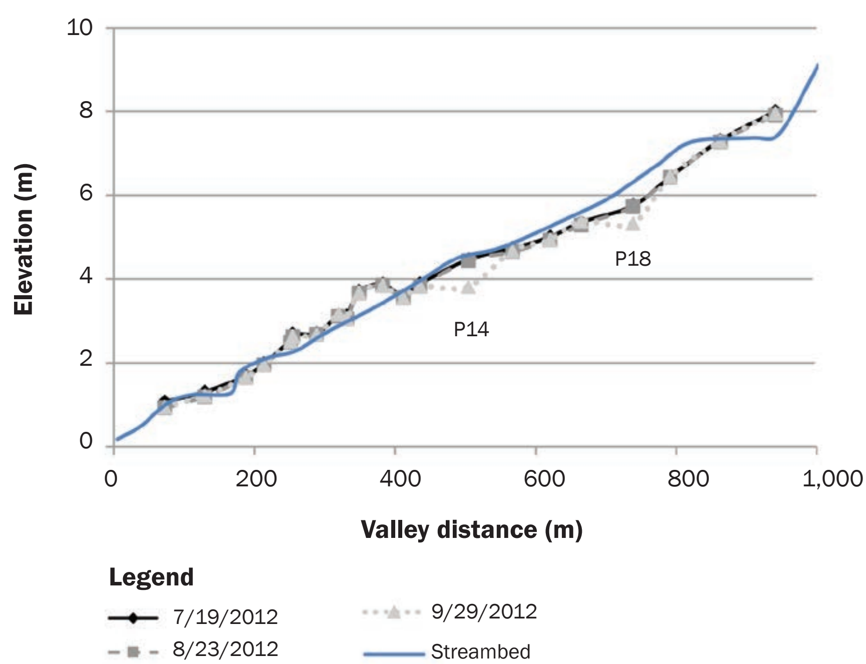


Table 2

Precipitation percentage of normal for four subbasins in northern California. Normal precipitation was calculated based on 30 years of precipitation data for the watershed area. Then precipitation for each water year of study was divided by the 30-year normal (PRISM Climate Group 2015).

	Precipitation percentage of normal (%)			
Watershed area	2011	2012	2013	2014
Little Truckee	150	64	80	65
Last Chance Creek	97	40	93	69
Lassen Creek	122	73	97	86
Carmen Valley	152	69	87	58

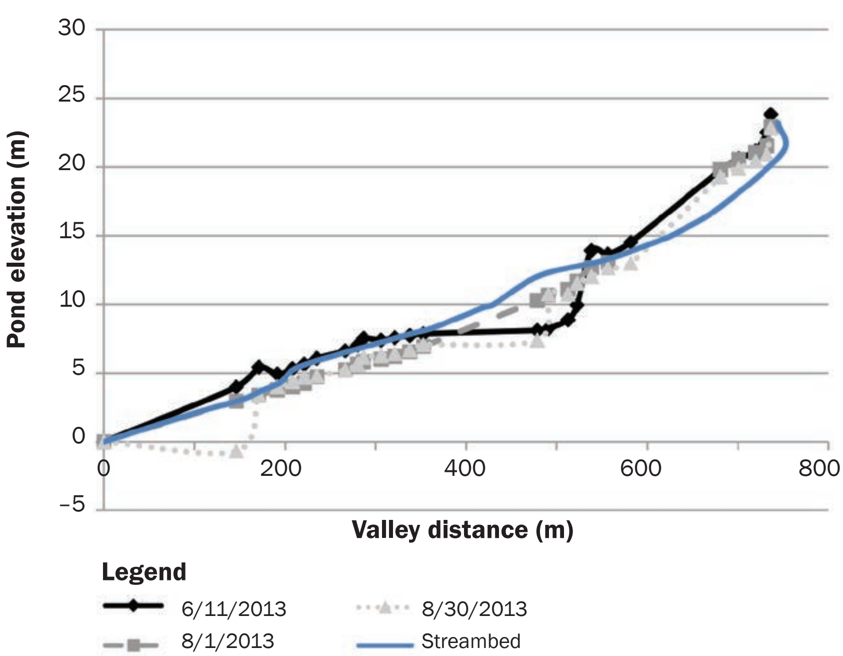
Table 3

The estimated direct evaporation from ponds, the estimated reference evapotranspiration (ET), and the area of each meadow.

Site	Estimated pond E_p (m^3) (June to October of 2012)	Estimated reference ET (m^3) (June to October of 2012)	Meadow area (m^2)
Big Flat	2,271	51,067	177,413
Davies Creek	109	5,919	18,313
Ferris Creek	1,354	56,217	203,167
Knuthson Meadow	5,364	246,195	953,892
Lassen Creek	4,149	65,612	171,972
Merrill Valley	714	62,490	239,141
Rose Canyon	1,654	56,286	135,212
Three-Cornered Meadow	2,792	45,860	109,271

Figure 5

Merrill Valley pond elevations in the summer of 2013. Pond elevation and valley distance are plotted starting from the downstream benchmark, which represents an elevation and a valley distance of zero. The three lines with symbols represent a different site visit, with a symbol for each survey date. The streambed generally runs alongside and not through the ponds.



Big Flat Meadow was one of the first meadows restored using the pond and plug technique. There was a large fluctuation in pond elevations (compared with other meadows). Several of the ponds drain or dry up late in the summer, evidence of the drain model. In the summer, ponds are perched above the water table and drain to groundwater. Big Flat Meadow also had a variable decline in pond elevations late in the monitoring season of 2013 (figure 9). The first visit of 2013 occurred in May and the meadow was saturated with water. By August some pond elevations had declined more than 2 m (6.56 ft), the upstream ponds had dried up, Pond 3 water was lower than in downstream Pond 4, and there was no flow in the majority of the stream channel.

The ponds at Three-Cornered Meadow had consistent elevation decline in the summer of 2013 (figure 10). The decline in ponds was greater than the estimated decline due to ET (table 3) and can possibly be attributed to the drain model. At the lower end of the meadow the ponds drop below the stream bed elevation, which may cause the stream to drain to the ponds.

Knuthson Meadow is downstream of Three-Cornered Meadow and the restoration design did not include a stream channel. The four most upstream ponds, as well as the five most downstream ponds, had minimal decline in the 2012 monitoring season (figure 11). The five ponds in the middle reach of the meadow had a greater decline over the 2012 monitoring season (figure 11).

Conceptual Model Classification. Using the hydrological evidence discussed in Results and Discussion, each meadow was classified into at least one conceptual model type (table 4).

Sponge Model. In the sponge model, storage of flood flows slows the transport of water and sustains pond elevations lower in the meadows and possibly sustains downstream flows into dry months (Tague et al. 2005; Hill 2011). Slowed transport of water through the meadow allows alluvial groundwater recharge. In the sponge model, springtime flows entering the meadow are temporarily stored and later released as lagged peak flows and base flow during the summer, as in Rose Canyon (figure 3; table 5).

Traits of the sponge model were present in four of the eight meadows (Big Flat, Davies Creek, Rose Canyon, and Lassen Creek) (table 4), were most significant in the spring,

Table 4
Rationale for linking conceptual models to meadows where appropriate. If a site does not fit into a particular conceptual model type then the area is left blank. ET is evapotranspiration.

Site	Sponge conceptual model	Valve conceptual model	Drain conceptual model
Rose Canyon	Discharge more variable upstream than downstream; prolonged downstream discharge.	Downstream discharge greater than upstream discharge; gaining meadow reach.	
Lassen Creek	Sustained pond elevations; dampened discharge peaks.	Lack of large pond level fluctuations.	Downstream discharge less than upstream discharge and greater seasonal fluctuation at two ponds.
Merrill Valley		Downstream discharge increases before upstream discharge, possibly due to groundwater discharge in the meadow. Elsewhere, there are no ponds that are above the streambed elevation.	In the midreach of the meadow, pond elevations drop below the streambed elevation, an indication of groundwater recharge.
Ferris Creek		Downstream discharge greater than upstream discharge; certain ponds more steady than wells in water elevation.	
Davies Creek	Upstream ponds start high and decline, more so than at bottom end.	Minimal pond decline (one pond).	Downstream discharge less than upstream discharge; large pond declines (more so than solely from ET).
Big Flat	Upstream ponds start high and decline, more so than at bottom end.		Large pond decline (more so than solely from ET).
Three-Cornered Meadow			Large pond decline (more so than would be expected based on ET estimates).
Knuthson Meadow		Minimal pond decline.	

and may appear as mostly subsurface storage due to current dry weather. Since bank full discharge and subsequent meadow saturation did not appear to occur during this study, water stored (via the sponge model) waned before the mid to late summer. Following wet winters (such as the winter of 2011) there may be more evidence of the sponge model through meadow outflow, which occurred at Rose Canyon (figure 3). In average and above average precipitation years there may be a longer period when evidence of the sponge model would persist, along with more groundwater discharge to the meadow when the water table is higher.

Valve Model. Groundwater discharging to the meadow in a localized area was evident in Merrill Valley, Knuthson Meadow, Davies Creek, and Ferris Creek. This localized upwelling can cause greater discharge below the meadow; examples of this occured at Merrill Valley, Ferris Creek, and Rose Canyon (figure 3).

The valve model suggests an explanation for diminished baseflow after restoration. Before incision, there may not have been baseflow below some valve meadows except in wet years. If ET water consumption in an unincised pristine meadow consumed the amount of incoming groundwater during summer and fall, water may not have escaped during these seasons. In an unrestored meadow with incision, water could flow quickly through the meadow without substantial ET loss. This could be the source of base flow experienced by downstream users in recent decades. Restoration that retains the water long enough to make it available to ET would reverse this process, consuming water. An example of a spring area in an incision converted to a pond is inferred from Ferris Creek (figure 6), Davies Creek (figure 7), and Knuthson Meadow (figure 11). A similar phenomenon could occur with an incision that captures water from general upwelling, such as occurred at Merrill Valley, that would allow water to discharge from the meadow as surface or baseflow, even if it previously went to ET. The same amount of water would be entering the meadow via groundwater recharge (springs, etc.); however, in an incised meadow, more water could leave through surface flow as opposed to ET. Restoration may enable the sponge model and extend flows from stored water for a time, but baseflow discharge would depend on total watershed discharge, sponge storage flux with lag effects, and meadow ET. In the meadows studied that exhibited traits of the valve model, groundwater storage gained through restoration varied (table 1).

The lack of pond water volume loss during the summer dry season in most ponds and especially lower ponds (table 5) indicates the sponge model. A lack in pond decline can also be attributed to groundwater inflow into the ponds (valve); Lassen Creek (figure 4) is an example of limited pond elevation fluctuation due to groundwater upwelling.

Drain Model. Ponds that act as drains may remain at a low level below the height of the plugs and during this drought have not been saturated by the meadow. In ponds 2, 3, and 4 at Davies Creek, water elevation drops below the stream bed and may recharge the groundwater. While some variation may be accounted for through ET, there is indication that percolation losses are also occurring, contributing to pond declines. Pond declines at Davies Creek (figure 8) suggest that there was water discharging to an aquifer, as explained by the drain conceptual model.

A large seasonal decline in pond elevations, more so than could be explained through ET

Figure 6
Ferris Creek groundwater and pond comparison. A dry pond or well is indicated by a gap in the data series. There are no data for the upper or lower pond after November 22, 2013, due to logger malfunction. Lower groundwater is found at the downstream end of the meadow and upper groundwater is found at the upstream end of the meadow. The lower pond is found at the downstream end of the meadow and the upper pond is found at the upstream end of the meadow. For the groundwater and pond elevations, all loggers were normalized for elevation in relation to the downstream benchmark.

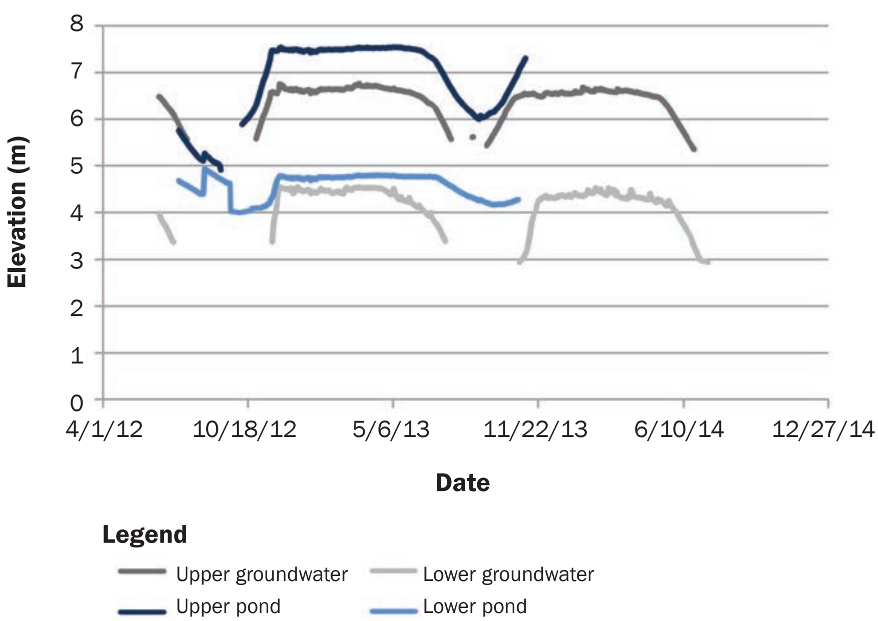
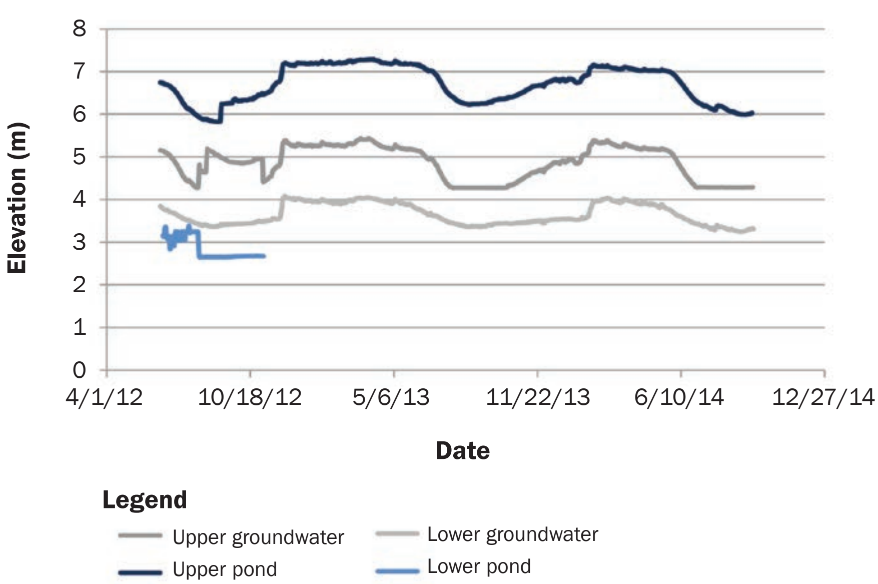


Figure 7
Davies Creek groundwater and pond comparison. Lower groundwater is found at the downstream end of the meadow and upper groundwater is found at the upstream end of the meadow. The lower pond logger was removed in the fall of 2012 and was not replaced due to low water levels. The lower pond is found at the downstream end of the meadow and the upper pond is found at the upstream end of the meadow. For the groundwater and pond elevations, all loggers were normalized for elevation in relation to the downstream benchmark.



alone (which occurred at Big Flat and Three-Cornered Meadow), may indicate ponds lose water to infiltration/percolation—the drain model. Big Flat pond elevations and groundwater elevations were linked, showing a net loss of water from all ponds due to infiltration losses (figure 9). Following restoration there was a substantial increase in available groundwater storage in Big Flat and Three-Cornered Meadow (figure 10), and these ponds may drain to shallow groundwater.

The Three-Cornered Meadow project may drain (figure 10) to the Knuthson Meadow project; the two projects are separated by a grade control structure and 500 m (546.81 yd) of stream channel. The Knuthson Meadow pond elevations do not decline nearly as much as at Three-Cornered Meadow (table 5) and could be recharged partially by the water draining from Three-Cornered Meadow and also from groundwater discharge to the Knuthson Meadow (figure 11; valve model).

Normalized Difference Vegetation Index and Evapotranspiration. Based on spatially averaged before and after NDVI values, NDVI values increased in all but one of 30 sites following restoration (figure 12). A paired *t*-test indicated a significant pre-post restoration NDVI increase of 0.076 ($p < 0.001$). The increase in NDVI at the eight sites studied in the conceptual model evaluation ranged from 0.06 to 0.15.

Estimated pond evaporation (Ep) is compared with estimated meadow ET (table 3). Meadow area is included in table 3 to give perspective of the size of the meadow. Percentage pond volume decline comparison for the summer of 2012 and 2013 (table 5) uses the area and elevation of each pond from the beginning and end of summer field visits. This study was conducted after an above-average precipitation year (2011) and during three below average precipitation years (2012 to 2014). The annual values of precipitation for water years 2011 through 2014 are compared to a 30-year average (table 2). Data on individual projects are presented in order as they appear in the Results and Discussion section, addressing the three conceptual models.

Satellite derived NDVI values provide an ET substitute because of the established relationship between ET and NDVI (Seevers and Ottmann 1994; Szilagyi et al. 1998; Szilagyi and Parlange 1999; Szilagyi 2002). Although NDVI is influenced by season, weather, plant community composition, topography, soils, etc., NDVI values show a statistically significant increase following restoration (figure 12). It is likely that ET increased with NDVI after restoration (Loheide and Gorelick 2005; Hammersmark et al. 2008). There was no clear connection between the amount of NDVI increase and the conceptual model type. This may be because many meadows exhibited mixed model response (table 4) or insufficient replication. The increase in NDVI following restoration indicates vegetation as a component of meadow water consumption.

Summary and Conclusions

This study expanded the current knowledge of restored meadow hydrology. Site selection enabled the use of study methods that require separation between ponds and restored streams, while still representing the general nature of the pond and plug projects as a population. Each site provided evidence of at least one of the three conceptual hydrologic models (sponge, valve, or drain) present somewhere in the project, and the majority of the sites had multiple models acting at different temporal and spatial scales.

This study was conducted entirely during a drought, especially in winter snowfall that drives surface water flow, and these results may not reflect nondrought conditions. However, with changing climates and precipitation patterns, these drought conditions may become more prevalent (Tague et al. 2005; Hammersmark et al. 2008; Lowry et al. 2010).

Localized order one soil classification and finer resolution geologic maps could be used to look for a link between model and soil type or underlying near surface parent material, faults, and springs. Springs occurring outside of the immediate project area could also be helpful for further investigation of the relationship between geology and meadow conceptual models.

In each meadow, climatic and locational factors influence meadow response to restoration. As expected, this led to variability in storage estimates, stream and groundwater hydrology, soil characteristics, and vegetation composition. The current rehydrated streams may vary in their state of resilience to the reestablished flow forces they will encounter; this geomorphic stability factor is the subject of a different study. Among sites there were variations in vegetation; despite these variations, NDVI generally increased following restoration. This NDVI indicated a recruit-

Figure 8

Davies Creek pond elevation changes in the summer of 2012. Pond elevation and valley distance are plotted starting from the downstream benchmark, which represents an elevation and a valley distance of zero. The three lines with symbols represent a different site visit, with a symbol for each survey date. The streambed generally runs alongside and not through the ponds. The darker triangle indicates a visit when the pond was dry.

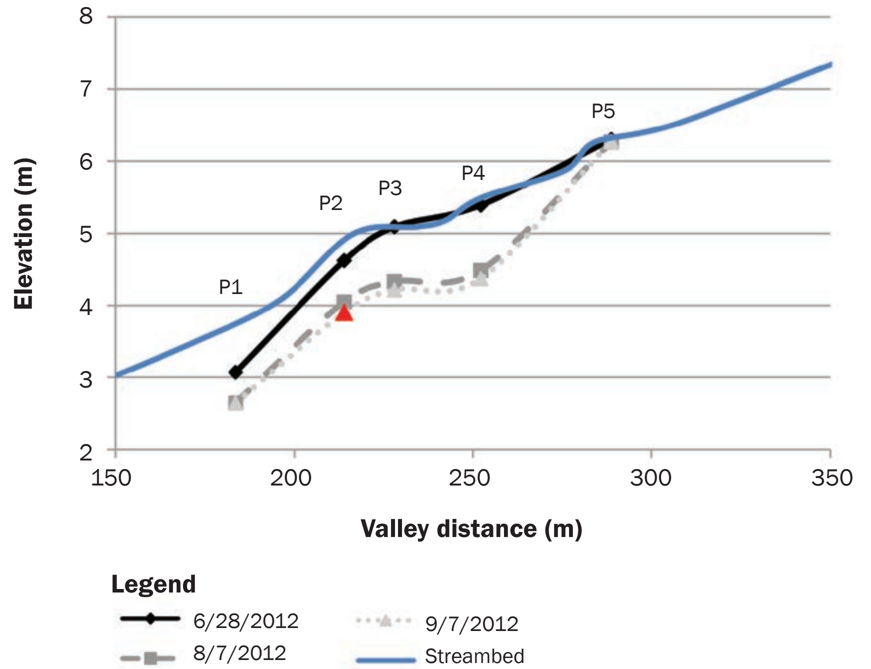


Figure 9

Big Flat Meadow pond elevation declines in the summer of 2013. The three lines with symbols represent a different site visit, with a symbol for each survey date. The large square indicates a visit (and elevation) where a pond was dry. The streambed generally runs alongside ponds and not through the ponds.

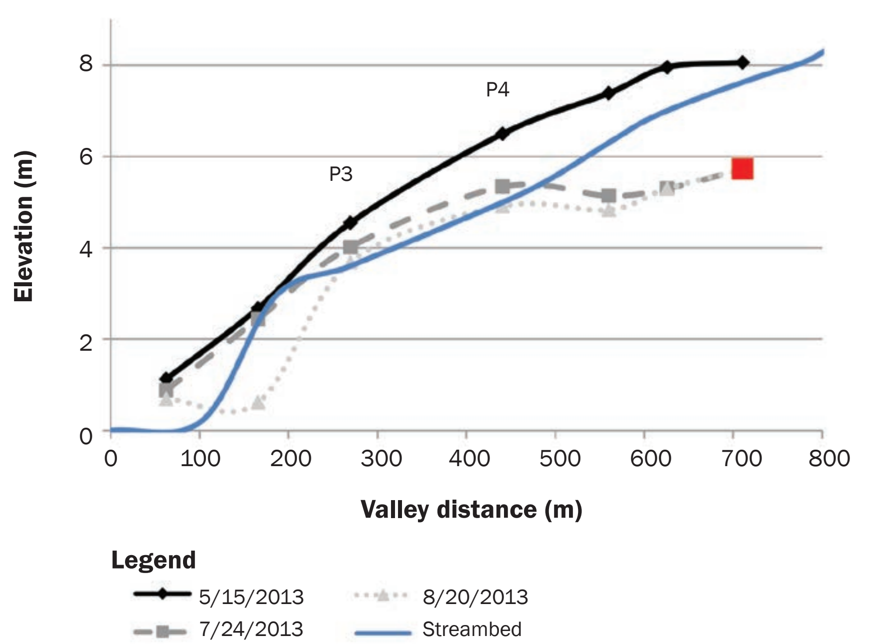


Figure 10
Three-Cornered Meadow pond declines for the summer of 2013. The three lines with symbols represent a different site visit, with a symbol for each survey date. The streambed generally runs alongside and not through the ponds.

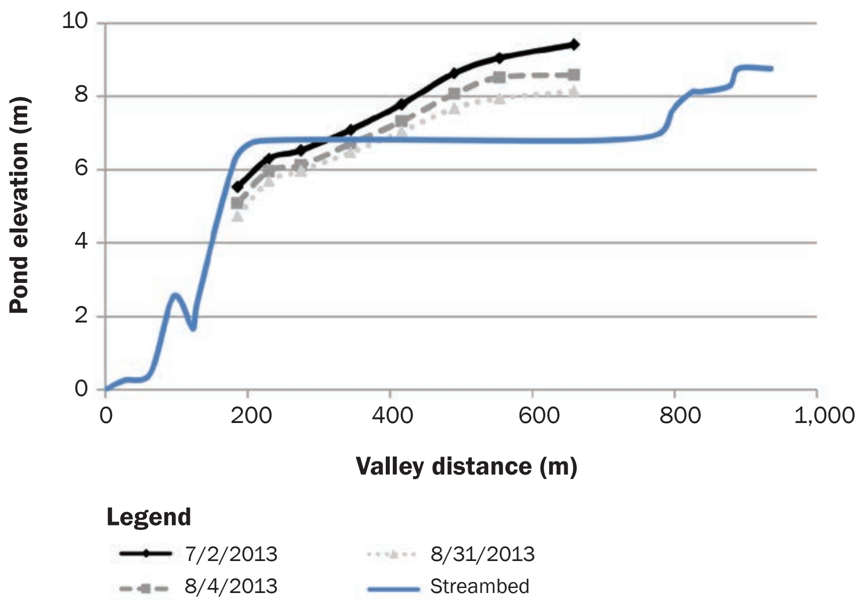


Table 5
Pond decline for 2012 and 2013 for each of the eight sites.

Site	Pond volume lost (%) 2012	2013
Big Flat	32.4	49.3
Davies Creek	91.1	71.6
Ferris Creek	77.4	77.3
Knuthson Meadow	30.8	40.6
Lassen Creek	18.3	12.8
Merrill Valley	38.9	54.4
Rose Canyon	47.2	44.9
Three-Cornered Meadow	64.6	64.8

ment of vegetation at the restoration site, a primary goal of restoration practitioners.

The spatial and temporal variability of the meadows made classifying each meadow into one model type a challenge. Five of eight meadows had traits consistent with multiple models. Conceptual model development did not always provide a clear division between meadow features and model type. Other meadow features (e.g., pond decline) were more indicative of model types expressed in the meadow.

Our use of multiple locations with inherent intersite variability and site-specific conditions provided us the opportunity to generalize our results to a larger set of meadows and projects in the region. The variability of meadows made classification into one conceptual model a challenge. Most meadows exhibited traits of multiple conceptual models on either a spatial or temporal basis.

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References

Abatzoglou, J.T. 2011. Development of gridded surface meteorological data for ecological applications and modeling. International Journal of Climatology 33(1):121-131.

Allen, R.G. 2013. Ref-ET: Reference evapotranspiration calculation (2013) Version 3.1.15 for Windows. http://extension.uidaho.edu/kimberly/2013/04/ref-et-reference-evapotranspiration-calculator/.

Allen, R.G., L.C. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. Food and Agriculture Organization (FAO) Irrigation and Drainage Paper 56. Rome: Food and Agriculture Organization.

Allen-Diaz, B.H. 1991. Water table and plant species relationships in Sierra Nevada meadows. The American Midland Naturalist 126:30-43.

Archbald, G. 2008. Using a Topcon Laser Level to Survey Elevation. San Francisco, CA: San Francisco State University.

Beamer, J.P., J.L. Huntington, C.G. Morton, and G.M. Pohll. 2013. Estimating annual groundwater evapotranspiration from phreatophytes in the Great Basin using landsat and flux tower measurements. Journal of the American Water Resources Association 49:518-533.

Debinski, D.M., M.E. Jakubauskas, and K. Kindscher. 2000. Montane meadows as indicators of environmental change. Environmental Monitoring and Assessment 64:213-225.

Dickard, M., M. Gonzales, S. Elmore, D. Leonard, S. Smith, J. Staats, P. Summers, D. Weixelman, and S. Wyman. 2015. Riparian area management: Proper functioning condition assessment for lotic areas. Technical Reference 1737-15. Denver, CO: US Department of the Interior, Bureau of Land Management, National Operations Center.

Elmore, W., and R.L. Beschta. 1987. Riparian areas: Perceptions in management. Rangelands 9:260-265.

Esri. 2013. ArcGIS Desktop: Release 10.2. Redlands, CA: Environmental Systems Research Institute.

Essaid, H.I., and B.R. Hill. 2014. Watershed-scale modeling of streamflow change in incised montane meadows. Water Resources Research 50:2657-2678.

Figure 11

Knuthson Meadow pond elevation changes in the summer of 2012. Pond elevation and valley distance are plotted starting from the downstream benchmark, which represents an elevation and a valley distance of zero. Each of the three grayscaled lines represents a different site visit, with a symbol for each survey date.

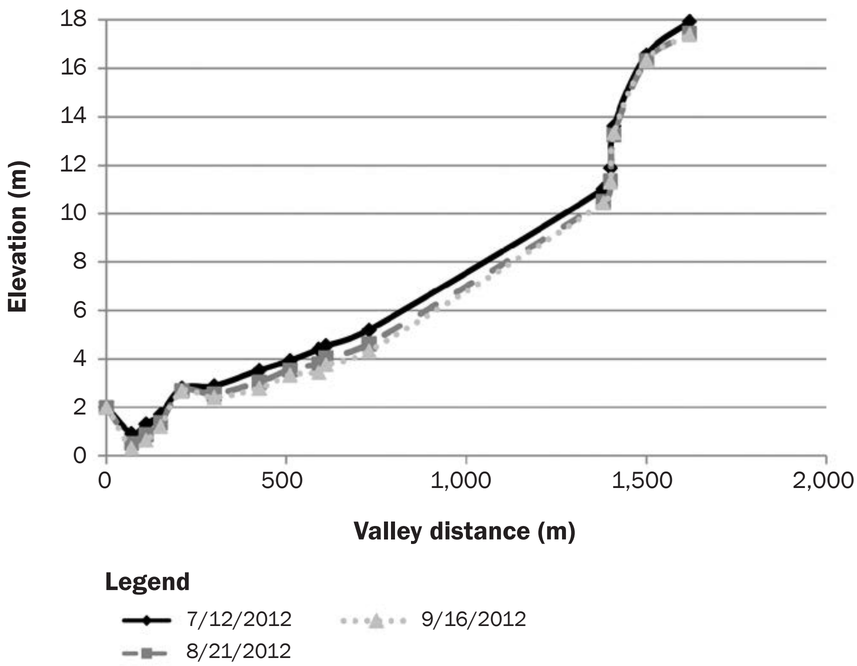
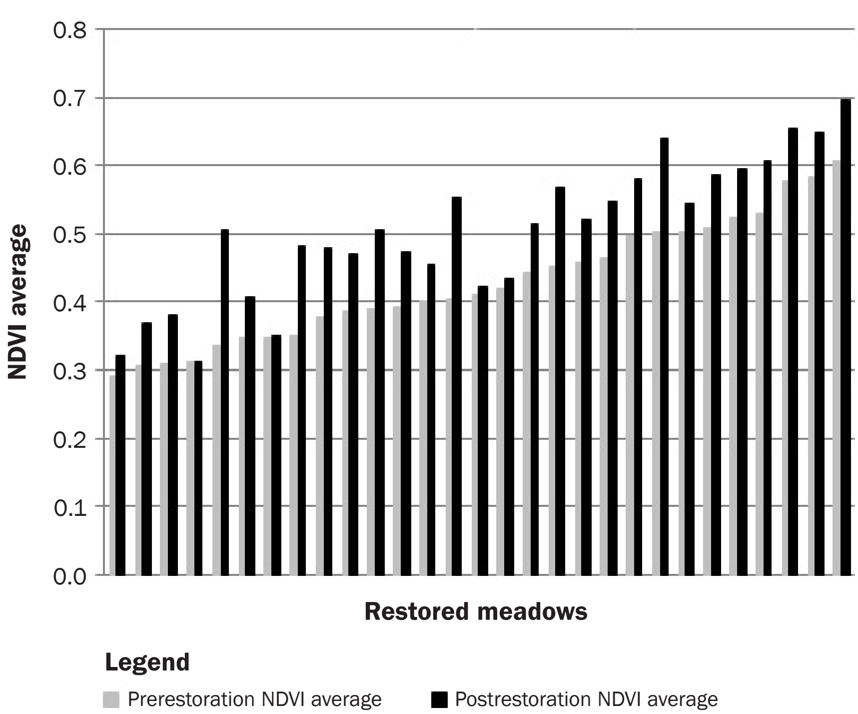


Figure 12

Pre- and postrestoration Normalized Difference Vegetation Index (NDVI) averages for 29 meadows restored with the pond and plug method.



Fetter, C.W. 2001. Applied Hydrogeology, 4th Ed., ed. P. Lynch. Upper Saddle River, NJ: Prentice Hall.

Hammersmark, C.T., S.Z. Dobrowski, M.C. Rains, and J.F. Mount. 2010. Simulated effects of stream restoration on the distribution of wet meadow vegetation. Restoration Ecology 18:882-893.

Hammersmark, C.T., M.C. Rains, and J.F. Mount. 2008. Quantifying the hydrological effects of stream restoration in a montane meadow, northern California, USA. River Research and Application 24:735-753.

Hammersmark, C.T., M.C. Rains, A.C. Wickland, and J.F. Mount. 2009. Vegetation and water-table relationships in a hydrologically restored riparian meadow. Wetlands 29:785-797.

Heede, R.H. 1979. Deteriorated watersheds can be restored: A case study. Environmental Management 3:271-281.

Hill, B. 1990. Groundwater discharge to a headwater valley, Northwestern Nevada, U.S.A. Journal of Hydrology 113:265-283.

Hill, B. 2011. Evaluating effects of meadow restoration on summer stream flows. USDA Forest Service. Presented at Meadow Restoration Informational Meeting, Quincy, California, February 3, 2011.

Hill, B. 2012. Sierra Nevada meadow hydrology assessment. Department of Water Resources State Water Plan Advisory Committee Meeting, Sacramento, California, December 13, 2012.

Hill, B.R., and S. Mitchell-Bruker. 2010. Comment on "A framework for Understanding the Hydrology of Impacted Wet Meadows in the Sierra Nevada and Cascade Ranges, California, USA": paper published in Hydrogeology Journal (2009) 17:229-246, by S.P. Loheide II and R.S. Deitchman. Hydrogeology Journal 18:1741-1743.

Johnson, A.I. 1967. Specific yield: Compilation of specific yields for various materials. Water Supply Paper 1662-D. Washington, DC: US Geological Survey.

Klein, L.R., S.R. Clayton, J.R. Alldredge, and P. Goodwin. 2007. Long-term monitoring and evaluation of lower Red River meadow restoration project, Idaho, U.S.A. Restoration Ecology 15:223-239.

Lindquist, D.S., and J. Wilcox. 2000. New concepts for meadow restoration in the Northern Sierra Nevada. Quincy, CA: Feather River Coordinated Resource Management Group.

Loheide, S.P., and E.G. Booth. 2011. Effects of changing channel morphology on vegetation, groundwater, and soil moisture regimes in groundwater-dependent ecosystems. Geomorphology 126:364-376.

Loheide, S.P., R.S. Deitchman, D.J. Cooper, E.C. Wolf, C.T. Hammersmark, and J.D. Lundquist. 2009. A framework for understanding the hydroecology of impacted wet meadows in the Sierra Nevada and Cascade Ranges, California, USA. Hydrogeology Journal 17:229-246.

Loheide, S.P., and S.M. Gorelick. 2005. A local-scale, high-resolution evapotranspiration mapping algorithm (ETMA) with hydroecological applications at riparian meadow restoration sites. Remote Sensing of Environment 98(2-3):182-200.

Loheide, S.P., and S.M. Gorelick. 2007. Riparian hydroecology: A coupled model of the observed interactions between groundwater flow and meadow vegetation patterning. Water Resources Research 43 W07414:1-16.

Lowry, C.S., J.S. Deems, S.P. Loheide, and J.D. Lundquist. 2010. Linking snowmelt-derived fluxes and groundwater flow in a high elevation meadow system, Sierra Nevada mountains, California. Hydrological Processes 24:2821-2833.

Lowry, C.S., and S.P. Loheide. 2010. Groundwater-dependent vegetation: Quantifying the groundwater subsidy. Water Resources Research 46:W06202.

NFWF (National Fish and Wildlife Foundation). 2010. Sierra Nevada Meadow Restoration Business Plan. http://www.nfwf.org/sierranevada/documents/sierra_meadow_restoration_business_plan.pdf.

Ohara, N., M.L. Kavvas, Z.Q. Chen, L. Liang, M. Anderson, J. Wilcox, and L. Mink. 2013. Modelling atmospheric and hydrologic processes for assessment of meadow restoration impact on flow and sediment in a sparsely gauged California watershed. Hydrological Processes 28:3053-3066.

Peters, A.J., M.D. Eve, E.H. Holt, and W.G. Whitford. 1997. Analysis of desert plant community growth patterns with high temporal resolution satellite spectra. Journal of Applied Ecology 34:418-432.

Ponce, V.M., and D.S. Lindquist. 1990. Management of baseflow augmentation: A review. Journal of the American Water Resources Association 26:259-268.

Prichard, D., F. Berg, W. Hagenbuck, R. Krapf, R. Leinard, S. Leonard, M. Manning, C. Noble, and J. Staats. 2003. Riparian area management: A user guide to assessing proper functioning condition and the supporting science for lentic area. Technical Reference 1737-16. Denver, CO: USDA Department of the Interior, Bureau of Land Management.

Prichard, D., C. Bridges, S. Leonard, R. Krapf, and W. Hagenbuck. 1998. Riparian area management: Process for assessing proper functioning condition for lentic riparian-wetland areas. Technical Reference 1737-11. Denver, CO: US Department of the Interior, Bureau of Land Management.

PRISM Climate Group. 2015. Parameter elevation Regression on Independent Slopes Model (PRISM) Climate Data. Corvallis, OR: Oregon State University. http://prism.oregonstate.edu.

Seevers, P.M., and R.W. Ottmann. 1994. Evapotranspiration estimation using a normalized difference vegetation index transformation of satellite data. Hydrological Sciences 39:333-245.

Soil Survey Staff. 2013. Web Soil Survey. USDA Natural Resources Conservation Service. http://websoilsurvey.nrcs.usda.gov/.

Szilagyi, J. 2002. Vegetation indices to aid areal evapotranspiration estimations. Journal of Hydrological Engineering 7:368-372.

Szilagyi, J., and M.B. Parlange. 1999. Defining watershed-scale evaporation using a normalized difference vegetation index. Journal of the American Water Resources Association 35:1245-1255.

Szilagyi, J., D.C. Rundquist, D.C. Gosselin, and M.B. Parlange. 1998. NDVI relationship to monthly evaporation. Geophysical Research Letters 25:1753-1756.

Tague, C., S. Valentine, and M. Kotchen. 2008. Effect of geomorphic channel restoration on streamflow and groundwater in a snowmelt-dominated watershed. Water Resources Research 44:1-10.

Tasumi, M., R.G. Allen, and R. Trezza. 2008. At-surface reflectance and albedo from satellite for operational calculation of land surface energy balance. Journal of Hydrologic Engineering 13:51-63.

TDS (Tripod Data Systems). 1999-2007. SOLO Field. Corvallis, OR: Tripod Data Systems, Inc.

USGS (US Geological Survey). 2015. The StreamStats program for California. Washington, DC: US Department of the Interior, USGS. http://water.usgs.gov/osw/streamstats/california.html.

Weisberg, P.J., S.G. Mortenson, and T.E. Dilts. 2012. Gallery forest or herbaceous wetland? The need for multi-target perspective in riparian restoration planning. Restoration Ecology 21:12-16.

Winter, T.C. 2007. The role of groundwater in generating streamflow in headwater areas and in maintaining baseflow. Journal of the American Water Resources Association 43(1):15-25.

WRCC (Western Regional Climate Center). 2013. RAWS USA Climate Archive. http://www.raws.dri.edu/.