# GEOMORPHIC, HYDROLOGIC AND ECOLOGICAL EFFECTS OF THE BEAR CREEK MEADOW RESTORATION PROJECT: A LAYMAN'S REVIEW

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**NOVEMBER 15, 2005**

# Introduction

Rivers and their floodplains throughout the world have been degraded by human uses including water extraction, river engineering, dam and levee building, and watershed land use changes. Two common causes of river degradation are overgrazing and the channelization of naturally flowing watercourses. Channelization is often performed in land reclamation activities or as a flood control measure. The combination of channelization and overgrazing is particularly destructive because it alters the functions of a riverine/floodplain wetland by impacting the hydrology, hydraulics, biogeochemistry, geomorphology, riparian ecology and aquatic ecology of the system. The growing recognition of the numerous functions and services that rivers and their floodplain wetlands provide, and the societal values placed on these functions, has prompted the restoration and rehabilitation of many of these degraded ecosystems in California, the United States and throughout the world. As several recent prominent publications have noted, it has been difficult to demonstrate 1) whether these ambitious and numerous restoration efforts have led to significant improvements in river functions and services and 2) which strategies have proven most effective. A dearth of rigorous pre- and post-project monitoring information and evaluations inhibits our ability to adaptively learn from projects and to improve and guide future restoration efforts.

This report describes an unusually well-documented stream restoration project on Bear Creek, a tributary to the Fall River in Shasta County, California. Extensive pre- and post-project information provides the opportunity to evaluate the response of Bear Creek ground water, surface water, geomorphology and wetland ecology to restoration of a 2.2-mile stream reach located on Thousand Springs Ranch. The methodology of the restoration is described, followed by a discussion of the geomorphic, hydrologic and ecologic effects observed during the comprehensive monitoring of the restoration project. The findings in this report indicate that efforts to restore ecosystem function within the Bear Creek Meadow by re-establishing the necessary geomorphic and hydrologic conditions have been successful with a concomitant range of ancillary downstream benefits.

# Background

Bear Creek Meadow lies at the base of the 84 square mile Bear Creek watershed, immediately upstream of the confluence with the spring fed Fall River (Figure 1). The watershed is underlain entirely by Tertiary and Quaternary volcanic rocks with a mixture of conifer forests, sagebrush scrub and, along the valley bottom, multiple meadows. Bear Creek Meadow on Thousand Springs Ranch is approximately two miles long and one mile wide and is flanked to the west by steep slopes, to the north and east by the low relief Medicine Lake Highlands, and to the southeast by the Fall River Valley. Located at the intersection of the Cascade Mountain Range and the Modoc Plateau, the vegetation surrounding the meadow is primarily Ponderosa pine forest interspersed with Black oaks and a shrub understory. The head of the meadow lies at the base of a relatively steep, heavily forested bedrock reach.

There is limited information available that indicates the conditions of Bear Creek Meadow prior to land use changes. A combination of historical aerial photographs, an undisturbed nearby "reference" meadow, and inspection of the relict undisturbed channels provide the best indications of pre-disturbance conditions.

Bear Creek Meadow was, and remains, a low-gradient meadow with a broad floodplain. The cohesive soils of the meadow indicate long-term accumulation of fine sediment associated with seasonal flooding. Radiocarbon dating of soil horizons in the center of the meadow indicate that this fine sediment deposition has been taking place for more than 2,800 years, reflecting long-term stability of the meadow system.

Analysis of historical aerial photographs and surveys of relict channels on Bear Creek Meadow show a complex pattern of channel development prior to human disturbances that included channel modification, grazing, dewatering and the introduction of invasive annual plant species. At the head of the meadow, where the confined bedrock channel transitions to a low-gradient alluvial valley, flows spread laterally into multiple, sinuous distributary channels that carried water and sediment across the meadow. During low flow periods, much of the creek's water flowed through one or two of these channels. However, during high rainfall or snowmelt periods each of the normally dry secondary channels "connected" to the primary channels. As the creek continued to swell with floodwaters, the many small channels would become full and the floodwaters would flow out of the creek's banks, inundating the meadow surface, Bear Creek's floodplain. During moderate to high flows, distributary channels would periodically be abandoned while new channels formed, typically due to large wood debris jams or sediment deposition. The channels of the meadow were all relatively shallow and many were lined with Oregon ash.

Although there is no direct evidence, it is apparent that Bear Creek Meadow played an important role in regulating the amount of sediment that Bear Creek discharged into the Fall River. Compared to the higher gradient, more confined upstream reaches of Bear Creek, the wide, low-gradient floodplain and channels of the meadow reduced the stream's ability to transport sediment immediately upstream of the Fall River. This reduction in sediment transport was due to the decrease in water depth and velocity as water spread out across the meadow. Anecdotal evidence suggests that the meadow historically "decanted" sediment that would have damaged spawning habitat in the spring-fed Fall River. This was especially important as human modification of the watershed upstream increased the stream's sediment load.

Although there has been logging, fire, grazing, road and railroad construction within the Bear Creek watershed for much of the last century, there is no information that would suggest a significant change in hydrologic conditions. The hydrology of Bear Creek is greatly influenced by the permeable soils that formed on top of the volcanic rocks throughout the watershed. Most precipitation, whether as rainfall or snow, reaches Bear Creek by first passing through the soils and rocks, rather than flowing across the surface. The transport of water through the subsurface prior to entering the creek acts like a shock absorber, causing the water to rise and fall slowly in response to typical storm or snowmelt events. The flood flows on Bear Creek are associated with intense rain-on-snow events in the winter and spring snowmelt events. During late spring and summer, flows on the creek steadily decline, usually stopping by June or July, which results in the drying out of portions of the meadow channel.

The combination of Bear Creek's shallow channels and extensive alluvial deposits overlying low permeability ancient lake deposits formed a very large, shallow aquifer. The aquifer was recharged every winter and spring by flows through and across the meadow along with minor inflow from the hills that surround the meadow. The shallow aquifer that existed within the meadow supported a lush wetland during the winter, spring and early summer, in turn supporting a complex mix of riparian, grassland and wetland vegetation. This mosaic of vegetation communities created an important feedback in the meadow. The dense vegetation slowed the velocity of water as it flowed across the meadow during floods, further enhancing the ability of the meadow to retain Bear Creek sediment, keeping it from Fall River.

Inspection of the aerial photographs and historical accounts, indicate that by 1960, the Soil Conservation Service and the landowner had realigned Bear Creek and cleared some vegetation to "reclaim" the meadow for the purpose of enhanced grazing and agriculture. These reclamation activities concentrated the many channels into one main channel and one secondary channel, which were partially straightened and located on the sides of the meadow. This was done to expedite floods across the meadow and to dry the meadow out. Physically, this realignment made Bear Creek follow a shorter path from the top of the meadow to the bottom, increasing the creek's slope in this reach. By increasing the channel's slope and eliminating the baffling effect of vegetation, the creek's "stream power," or the ability of the stream to erode, was also increased. In this altered state, the increased power of Bear Creek initiated an extended period of incision within the meadow.

First cutting down, the creek became deeper and deeper, which allowed it to convey more and more water within its banks rather than gently across the floodplain. Subsequently, its ability to erode also continued to increase. As it eroded, Bear Creek became progressively disconnected from its floodplain in all but the largest of floods. By 1999 the channels had incised up to 15 feet into the alluvium. This incision led to the near complete loss of in-stream spawning habitat, a significant lowering of the ground water table, and the loss of riparian and meadow plant communities. Channel incision not only eliminated the meadow's ability to trap sediment, but led to substantial increases in the amount of sediment delivered to the Fall River by channel erosion.

Prior to channel realignment, the ground water table was very close (0-3 ft deep) to the meadow surface during the spring and early summer. Once Bear Creek incised, the ground water table was much deeper (3-5+ ft deep) in spring and early summer. Consequently the water dependent wetland plant species, which historically created a riparian corridor lining and stabilizing the banks of Bear Creek, were no longer able to persist and gave way to annual grasses characteristic of much drier upland habitats.

As the stream channel incised and lowered the ground water table, the stream banks progressively grew very tall and steep, and unable to support much vegetation which lead to increased instability of the stream banks (Figure 2). This instability initiated a cycle of lateral erosion of the banks, widening the channel. This lateral channel enlargement confined more water within the channel and contributed even more sediment to the Fall River. Bear Creek's once numerous shallow, vegetated, and meandering channels had degraded into what are best described as two unstable, erosive gullies (Figure 2).

By the 1990's Bear Creek's main channel through the meadow, the gully, continued to erode vertically and laterally. According to pre-restoration project sediment flux monitoring conducted by Rick Poore, the meadow was delivering copious quantities of sediment downstream to the Fall River. In addition, the historic ecological processes that sustained the meadow were fundamentally altered. The Oregon ash trees, which lined portions of the undisturbed channels, existed in a state of poor health. New ash trees ceased to regenerate. The multitude of native wetland plant species, including various species of sedges and rushes, were present in very limited amounts. Exotic annual grasses like Japanese brome, bulbous bluegrass and Kentucky bluegrass, common in upland (non-wetland) environments dominated what little vegetation was present on the meadow surface. In addition, due to the very wide nature of the channel, fish passage through the meadow was limited only to periods of higher discharge.

## Details of the Restoration

Driven by a desire to improve the degraded creek and meadow and to reduce impacts on the Fall River, the landowner, Peter Stent, undertook a multi-year program to restore the historic geomorphic, hydrologic and ecologic processes that sustain healthy meadow and creek ecosystems. The founder of modern fluvial geomorphology, Luna Leopold, and a highly experienced stream restorationist, Dave Rosgen, were recruited to participate in the planning of the restoration. Together, Leopold and Rosgen prescribed a four year pre-project research plan which included monitoring aspects of hydrology and sediment transport along with geomorphic surveys at the project site and a reference site. This pre-project data collection began in 1994, five years before the actual restoration was undertaken. Both Peter Stent, the Thousand Springs Ranch owner, and Rick Poore, the Thousand Springs Ranch manager, attended many of Dave Rosgen's stream restoration courses. Rick Poore used the Bear Creek Meadow Restoration as his design project throughout the series of restoration courses. During the design process, Dave Rosgen visited the site, reviewed the plan and utilized his extensive experience to suggest any concerns or potential modifications.

A wide variety of analyses were conducted to provide a vision for the restored channel. Briefly described below, this list is by no means complete or all-inclusive. Historical aerial photographs were collected and analyzed. Natural (undisturbed) channels, which remained in the Bear Creek Meadow, were surveyed to assess their geometry and discharge capacity. A "reference reach," located several miles upstream in a relatively undisturbed meadow was analyzed, and various data collected. In addition, creek discharge and sediment load were measured at the top and bottom of the meadow. As these data were collected and analyzed, a vision of Bear Creek in its restored state began to emerge. Following completion of the design for restoration, a panel of experts reviewed it and recommended its implementation.

The creek and meadow restoration construction began in the early summer of 1999. The project employed a popular methodology (frequently used by Rosgen and his trained stream restoration practitioners) known as "pond and plug." Discrete sections of the disturbed channel or gully were plugged with soil while a new channel was constructed nearby. If the plugs were not placed in the old channel, the restored channel might show a tendency to be abandoned as flow returned to the older channel during high flow events. The fill material needed to create these plugs was derived from nearby floodplain deposits, creating several large ponds within the meadow. The restored channel was constructed using remnant channel reaches where available and practical, and the remaining reaches were sculpted with heavy machinery in the size and shape of the historic meadow channels (Figure 3). Based upon the recommendation of the expert panel, gravels were added to the restored channel to enhance fish spawning habitat and to reduce bed erosion. Upon the completion of the project, 2.2 miles of restored stream, and 42 acres of new ponds, almost ten percent of the meadow area, existed in the Bear Creek Meadow (Figure 4). These ponds consisted of two types: large ponds created by the need for fill material, and smaller linear ponds, which are remnants of the old gullies.

Immediately following the sculpting of a restored reach, it was heavily planted with a variety of wetland plants (grasses, sedges, rushes, willows, and various tree and shrub species), to resist erosion, and accelerate the recovery of the riparian corridor. Once planted, these plantings were irrigated to encourage root growth and successful establishment. Nearly all of the genetic material for planted vegetation was collected from the meadow in the years preceding the earthwork. Plants were generated and grown off site at Cornflower Farms, a nursery specializing in native vegetation restoration projects. By the fall of 1999, prior to arrival of winter rains and flow through the newly constructed channel, over 109,000 native herbaceous plants (mostly sedge and rush species) and 4,500 native trees and shrubs had been planted in the meadow.

## Effects of the Restoration

The goal of the restoration of Bear Creek Meadow was to set the meadow ecosystem on a trajectory where the natural hydrologic, geomorphic and ecologic processes could sustain the ecosystem without the need for frequent intervention. In the six years following the restoration, many elements of the creek and meadow have been monitored. Monitoring information has been collected by Streamwise, Inc., the Center for Watershed Sciences at the University of California, Davis, CalTrout, California Department of Fish and Game, Cornflower Farms and Point Reyes Bird Observatory. It is arguably one of the best-monitored private stream restoration projects in the United States. The discussion below provides a partial synopsis and an assessment of the effects of the restoration on the geomorphic, hydrologic and ecologic processes in the meadow.

The conceptual foundation of the restoration project centered on the assumption that recreating natural geomorphic functions of the floodplain and channel would lead to restoration of desired ecologic conditions. These functions included 1) development of a sinuous meadow channel with the proper size and geometry to contain and convey low to moderate flows without excessive erosion or sedimentation, 2) promotion of frequent overbank flooding of the meadow in order to support meadow wetland and riparian communities, reduce the erosive effects of high flows on the channel, and trap sediment on the floodplain, and 3) establishment of a channel geometry that enhances connection and interaction between surface water flows and ground water in the meadow, restoring shallow ground water conditions. This effort ultimately seeks to restore a condition of “dynamic equilibrium,” where the size, shape and adjustments of the channel are in balance with the sediment and water supplied to the meadow by the watershed.

## *Geomorphic Response*

The plugging of the old, over-sized channel and creation of the new, small main channel for Bear Creek re-established the geomorphic processes typical of a meadow. Based on annual surveys of more than 20 channel cross sections (Figure 5), the sinuous, shallow channel has remained relatively stable in the period since completion of the restoration project. Rapid channel adjustments involving incision or significant lateral migration have not been widespread although minor redistribution of sediment has been observed. The causes of this sediment redistribution are under investigation by UC Davis and Streamwise, Inc., but appear to involve local excessive slope or flow confinement. The few instabilities have been addressed by Streamwise, Inc. through a variety of bank stabilization techniques.

The relatively shallow, low gradient channel of the restored meadow has played an important role in regulating sediment flux into Fall River. In the years immediately following completion of the project, widespread deposition of silt and sand was noted on the floodplain in the lower reaches of the project. Under pre-project conditions, this fine sediment would have been confined to the main channel and transported directly to the Fall River. The restored meadow appears to be effectively trapping large volumes of sediment that would normally have impaired the Fall River. This stems from the ability of the channel to maintain high enough turbulence to keep sediment in suspension as flows leave the channel and move onto the floodplain. Once flows move onto the floodplain, wetland and riparian vegetation slow the flows, allowing sediment to settle. Over the course of the spring and summer, vegetation establishes on the newly deposited sediment, trapping it on the floodplain. Sediment flows into, and out of, the meadow have been closely monitored. During the high flows of 2005, sediment concentrations entering the meadow were four times greater than those exiting the meadow, indicating the exceptional benefit that the restoration project provides to the Fall River.

## *Hydrologic Response*

The restoration of the Bear Creek channel has profoundly impacted the hydrology of the meadow. By reducing the channel slope and size, the creek discharges water onto the floodplain with much greater frequency. Under pre-project conditions, overbank flooding occurred only when inflows to the meadow were greater than 1,200 to 1,500 cfs. In the post-project condition, floodplain inundation begins when inflows exceed 130 cfs. This order of magnitude difference has significantly changed the frequency of flooding.

As floodplain inundation occurs, floodwaters are slowed and temporarily stored on the meadow surface before either flowing back into the channel at a downstream location, or infiltrating into the meadow, recharging the ground water table (Figure 6). One effect of this restored connection between the channel and the floodplain has been that downstream flood peaks, or the elevation of floods, have been significantly reduced. In addition, due to temporary storage of floodwaters on the floodplain, the length of time that it takes for a flood pulse to move through the meadow increased substantially, enhancing the amount of recharge to shallow ground water. Therefore, while softening the impact of floods, the restored channel-floodplain connection has also greatly enhanced ground water conditions. Quantifying the magnitude of these changes is the subject on going research by UC Davis researchers; however some preliminary results illuminate some anticipated trends (Figure 7).

In the pre-project state, the deeply incised gully intercepted the ground water table and effectively drained it (Figure 8). The ground water surface sloped toward the gully and, during low flow conditions; ground water would discharge into the gully and be carried into the Fall River. Plugging the gully with soil eliminated this ground water drain, allowing the ground water table throughout the meadow to recover. This coupled with the frequent flooding of the floodplain and recharge of the meadow aquifer through the relatively shallow restored channel has restored ground water throughout the meadow to conditions that are roughly similar to those prior to channelization. Preliminary calculations indicate that currently during the spring, the meadow stores 195 acre-feet of water more than it did during pre-project conditions (an acre-foot is 325,851 gallons of water, roughly equivalent to the water necessary for a single household for one year).

## ***Ecologic Response***

The restoration of channel geomorphology and surface water-ground water connections has provided the physical processes necessary for the recovery of the meadow's plant and animal communities. The complexity and extent of ecologic recovery of the meadow is beyond the scope of this report and is the focus of on-going study by UC Davis researchers. Several key elements of the recovering meadow and stream ecology have been chosen for this discussion. Passive elements are emphasized, because in many ways the meadow is restoring itself now that the historic physical processes have been reestablished.

While extensive planting occurred along the stream corridor in 1999 for immediate post-construction stabilization, the effects of the restoration of physical processes that extend throughout the meadow go far beyond the planting zones. These vegetation effects can be separated into those of woody plants and those of herbaceous plants. The ribbons of Oregon ash trees, which lined portions of the historic channels, have regained their vigor and produced large quantities of seeds in the years following the restoration. Many young ash trees have recruited naturally within the riparian zone, and have survived through their first few crucial years of life. The vast majority of willows that were planted have grown quite successfully. Willows also have grown from plant material washed downstream and deposited on the floodplain as floodwaters recede. Many new willow individuals have been observed throughout the meadow, the result of beaver activity upstream. It will take many years before the woody plants have grown enough to provide habitat and forage for the variety of animals, which utilize them, but the trajectory observed over the past six years is encouraging. In addition, xeric (dry) woody plants (i.e. great basin sage) that had colonized the driest upper portion of the meadow have died from the frequent flooding and shallow ground water conditions.

Herbaceous (non-woody) plants have responded dramatically to the restoration activities. A vast seed bank existed throughout most of the meadow, allowing most historic species to propagate themselves given the restored water regime. Vast areas previously consisting of scarce quantities of exotic annual grasses have been reclaimed by native wetland plant species. Through many of the wetter areas of the meadow, sedges, rushes and native wet meadow grasses dominate at high biomass levels. In addition, species common to vernally wet places (i.e. vernal pools and depressions) are found in great abundance in some areas. This is a direct result of the reconnection of Bear Creek to its floodplain. The impacts of this restoration on herbaceous plants are best seen in early June when an exceptional display of a variety of native wildflowers occurs due to the increased soil moisture (Figure 9).

The aquatic ecosystem has also rebounded, with a diverse range of aquatic animal species utilizing the restored ecosystem. Several native fish species, including Sacramento sucker, rainbow trout and Sacramento pike minnow (previously known as squawfish) have been observed in large numbers within the restored channel. No systematic spawning surveys have been recorded, however the physical conditions (combination of depth, velocity, substrate size, and permeability) in many of the restored reaches are ideal for the spawning of suckers and trout. The fish are regularly observed using the restored reach as a corridor to migrate upstream for spawning. Fish are best observed in the creek in early June as juvenile trout migrate downstream to the Fall River as Bear Creek's flow declines.

The ponds, created by channel plugging and excavation for fill material, have added an additional seasonal lentic type of aquatic habitat not historically abundant on the Bear Creek Meadow. It is not known whether the introduction of these new ecosystem elements has a positive or negative impact on the overall meadow ecosystem. In all, 42 acres of ponds are found in the meadow, existing in a variety of shapes, sizes and depths. In late summer, all but a few of these ponds are totally dry, reflecting the seasonal draw down of ground water in the meadow. As the creek begins to flow in late fall/early winter these ponds begin to fill as the shallow ground water table starts to rise. These seasonal ponds provide habitat for several native amphibian species including Pacific treefrogs and Western toads. The ponds are ephemeral, however they remain wet long enough for treefrogs to hatch from their eggs and metamorphose into froglets. In fact, the ephemeral nature of the ponds is an advantage for the treefrogs because if water was permanently present, then predators (bullfrogs and fish) would also be present. In early summer, treefrogs are conspicuously abundant around the perimeters of many of the created ponds. As the ponds dry up, the frogs appear to move into the neighboring ribbons of ash trees to live their adult lives.

The created ponds and surrounding wet meadow areas also provide seasonal habitat to large numbers of waterfowl as they migrate through the area. Mallards, Wood Ducks, Cinnamon Teal, Gadwalls, American Widgeons, Mergansers and Canada Geese have all been observed using the ponds. Waterfowl are not the only birds found in the restored meadow. Wilson's Snipe, a shorebird associated with very wet meadows, was found in high numbers by a Point Reyes Bird Observatory (PRBO) survey conducted in June of 2005. Typically they probe into the mud for invertebrates and nest just off the ground in thick herbaceous vegetation (primarily sedges). In addition, Song Sparrows, which are associated with sedges and other dense herbaceous vegetation along creeks in this region, were found to be increasing in abundance following completion of the restoration. While the meadow still falls behind undisturbed meadows surveyed by PRBO in the nearby Lassen National Forest, increases in both relative abundance and species richness have been documented following the restoration. It should be noted, that the meadow's woody vegetation is still considered immature, as it takes in excess of ten years for riparian tree and shrub species to reach the structural diversity observed in undisturbed meadows. It is expected that relative abundance and species richness will continue to increase as the existing woody vegetation matures, new willow clusters are planted, and new tree and shrub individuals are naturally recruited, which will increase the structural diversity of habitat available to birds.

Ecological effects of the restoration extend beyond those discussed above. Although it has not been documented, the lush restored meadow also provides important terrestrial habitat to many animal species including elk, deer, coyotes, bobcats, mountain lions, in addition to Sandhill Cranes and several species of raptors.

## Conclusion

The foundation of the Bear Creek Meadow Restoration Project was to restore the geomorphic and hydrologic conditions necessary to recover and sustain plant and animal communities typically associated with wet meadows and to reduce the impacts of channel erosion on the Fall River, downstream of the project. The plugging of the incised gullies and the construction of a shallow, sinuous meadow channel in 1999 appears to have initiated a significant and rapid recovery of the meadow. Based on study of the meadow over the past six years, the following have been well-documented:

- significant reduction in sediment supplied to Fall River by incised gully erosion
- increased effectiveness of sediment trapping by the floodplain, further reducing sediment loads to the Fall River
- increased frequency and duration of seasonal meadow flooding
- restoration of shallow ground water conditions with significant increases in soil moisture
- recovery of woody vegetation along historic and restored channels and decline of invasive, dry-meadow woody vegetation
- dramatic recovery of herbaceous plants, particularly native wetland plant species
- increases in use of the meadow by birds, including species common to wet meadows

Less well-documented but generally observed responses include:

- improved native fish rearing habitat and connection to the upper watershed
- significant increase in habitat for native amphibians and waterfowl

The extensive monitoring of the Bear Creek Meadow Restoration Project provides a rare opportunity to evaluate the effectiveness of restoration efforts of this type. The results of the monitoring effort and a complete assessment of the impacts of the project are currently being prepared by Christopher Hammersmark of the UC Davis Center for Watershed Sciences. This effort, funded by the David and Lucile Packard Foundation, the Peter and Nora Stent Foundation, and the University of California Center for Water Resources, should be completed in 2007.

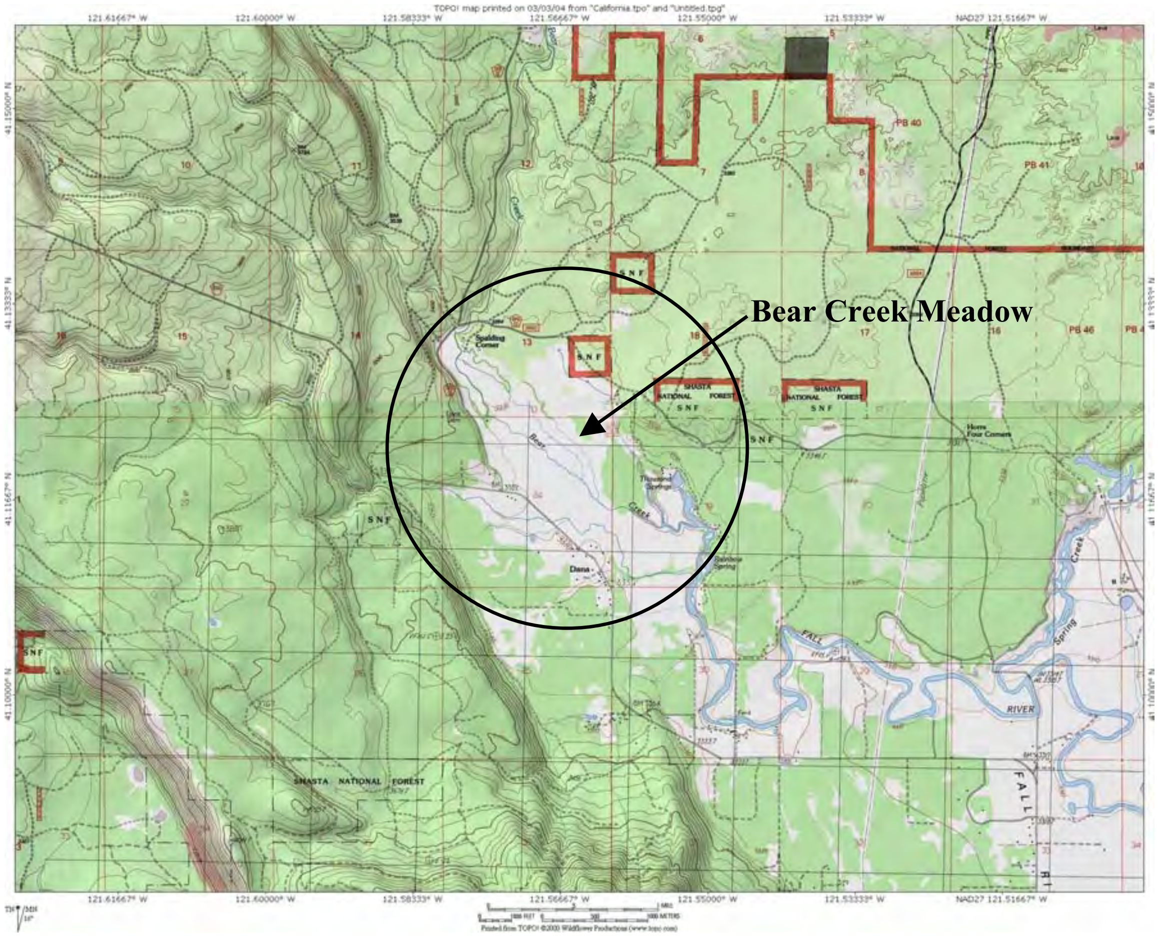

**Figure 1 –** Bear Creek Meadow location map. The 2.2 mile restored reach is just upstream of the Bear Creek-Fall River confluence in northeastern Shasta County, California.

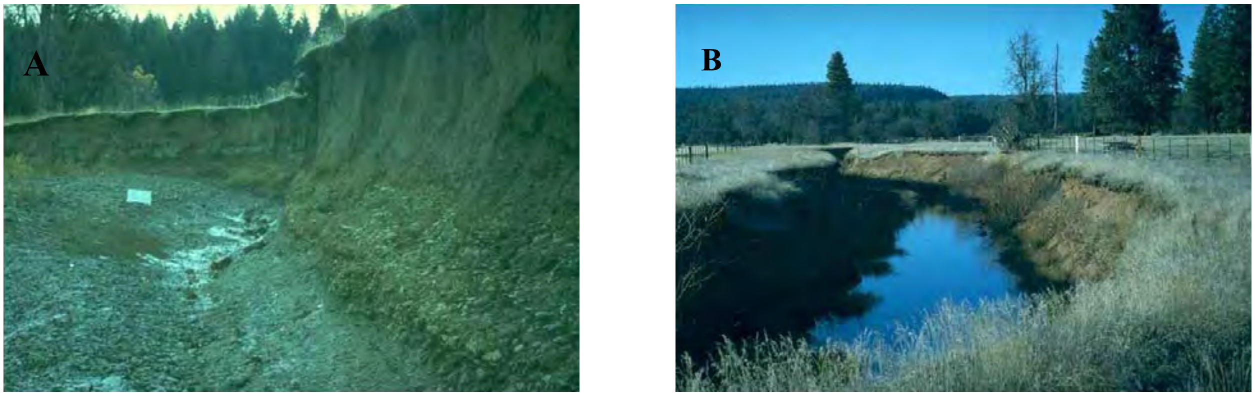

**Figure 2 – A)** Tall, near vertical unvegetated banks of the pre-restored Bear Creek channel. **B)** Prior to restoration, Bear Creek was best described as a gully (Photos: Rick Poore).

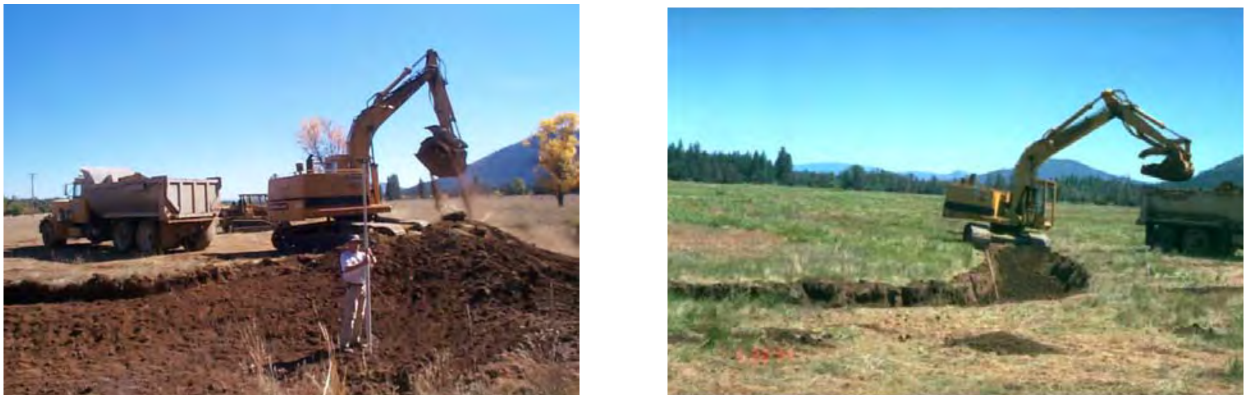

**Figure 3 –** Sculpting the restored channel in the summer of 1999 (Photos: Rick Poore).

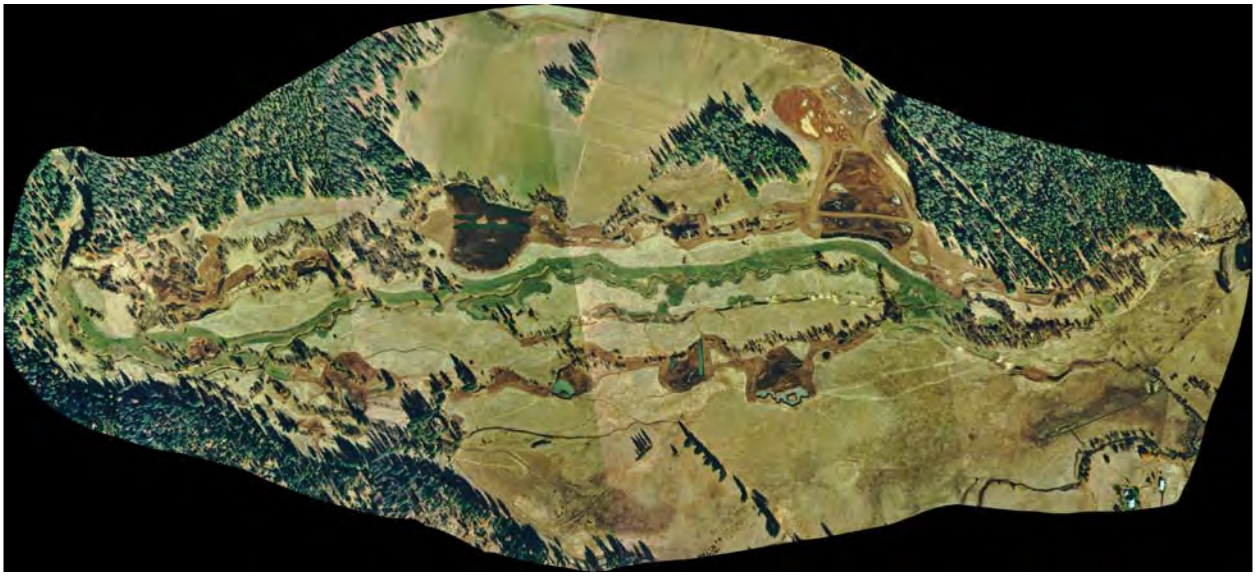

**Figure 4 –** Aerial view of the Bear Creek Meadow taken in the fall of 1999, months after the construction portion of the restoration was completed. The green irrigated strip running through the middle of the meadow highlights the restored channel. The "plugged" main and secondary channels, and source ponds are distinguished by the brown color of their unvegetated earth (Photo: Hodges Aerial Photos).

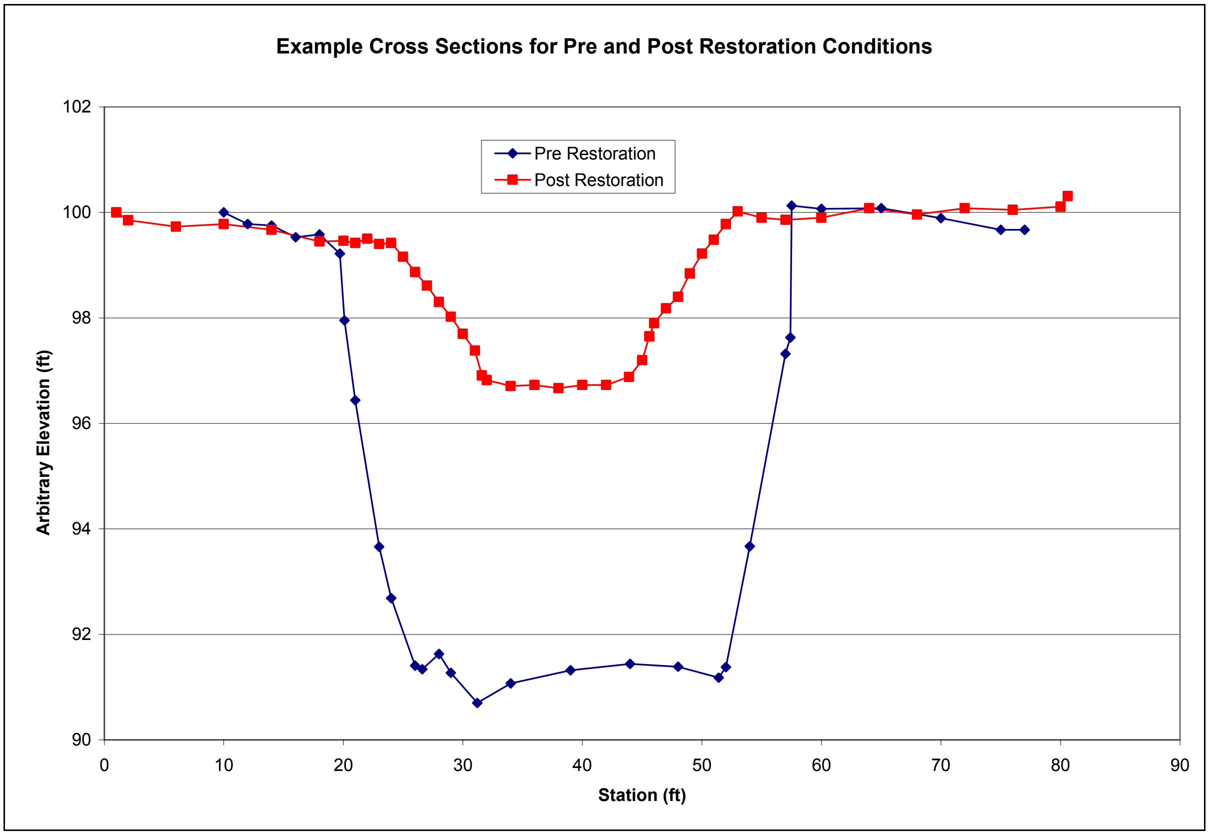

**Figure 5 –** Representative cross sections of Bear Creek in the pre restoration (blue with diamonds) and post restoration (red with squares) project conditions. Notice how much larger (deeper and wider) the pre restoration channel is when compared to the restored channel.

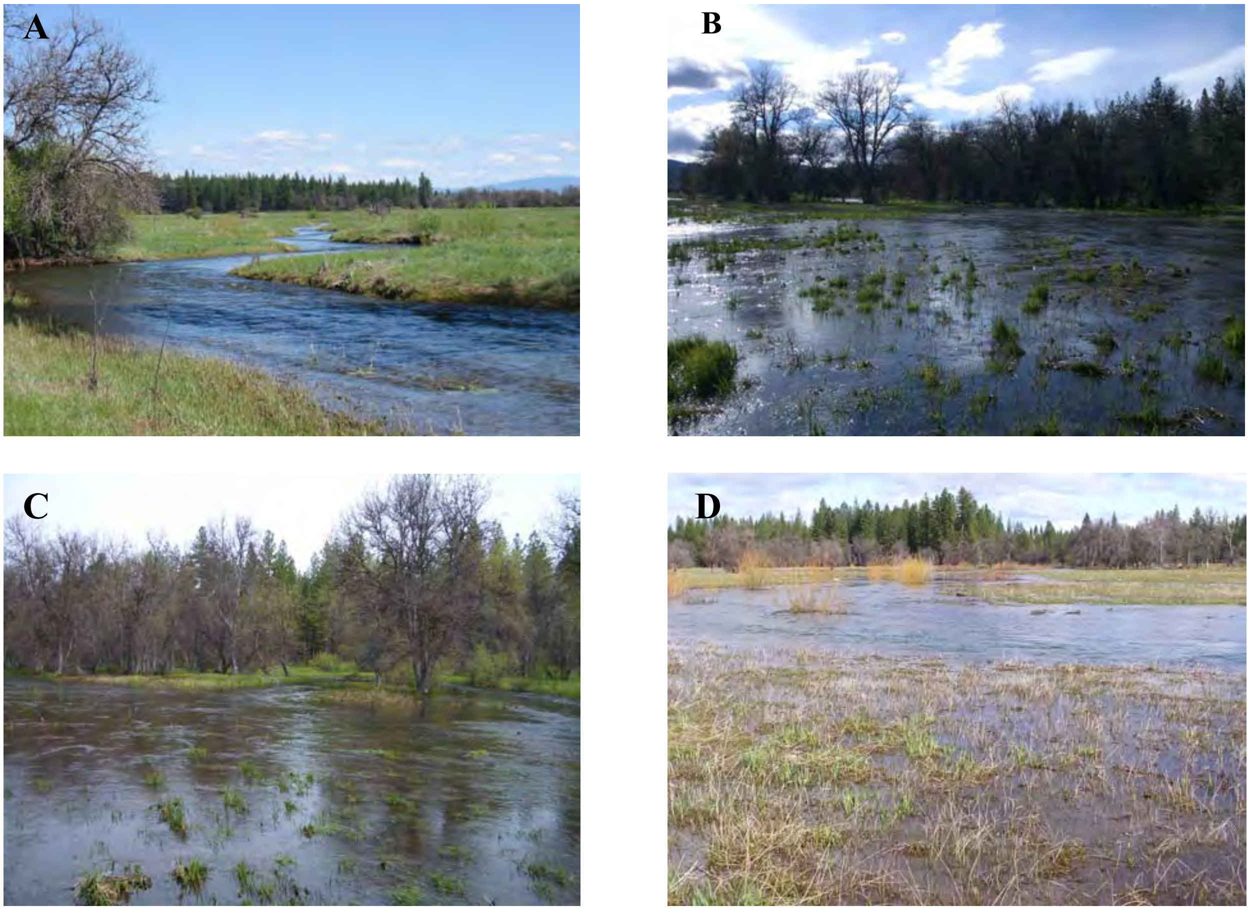

**Figure 6 – A)** The restored Bear Creek channel flowing just below bankfull. If discharge in the creek increased, the creek would flow out of banks and begin to inundate the floodplain (Photo: Steve Winter). **B-D)** The restored Bear Creek channel during flood conditions. In the restored state, floodwaters are able to frequently inundate the floodplain, dissipating energy, depositing fine sediment and recharging the shallow water table (Photos: Chris Hammmersmark).

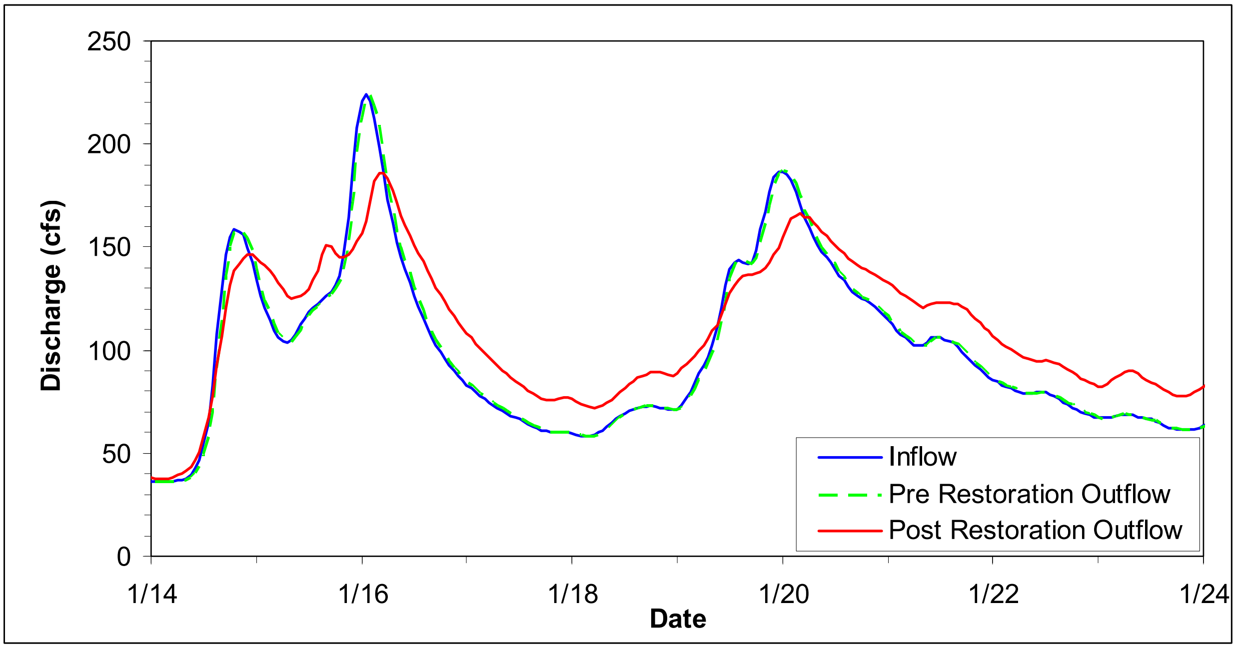

**Figure 7** – Preliminary hydraulic modeling results reveal the effect of the channel restoration on the movement of several flood pulses through the meadow. In the pre-project incised condition (green dashed line) each flood pulse travels through the meadow relatively unchanged. In this case the meadow outflow (green dashed line) is very similar to the meadow inflow (blue solid line). Due to a lack of floodplain connectivity in the incised condition, flood peaks maintain their magnitude and travel through the meadow rather quickly. In the post-project, restored condition, significant attenuation and peak reduction are observed in the meadow outflow (red solid line). As water leaves the main channel and inundates the floodplain, it is slowed and temporarily stored. While some of this water flows back to the channel downstream after flowing across the floodplain, some of the water infiltrates into the meadow surface and recharges the shallow water table.

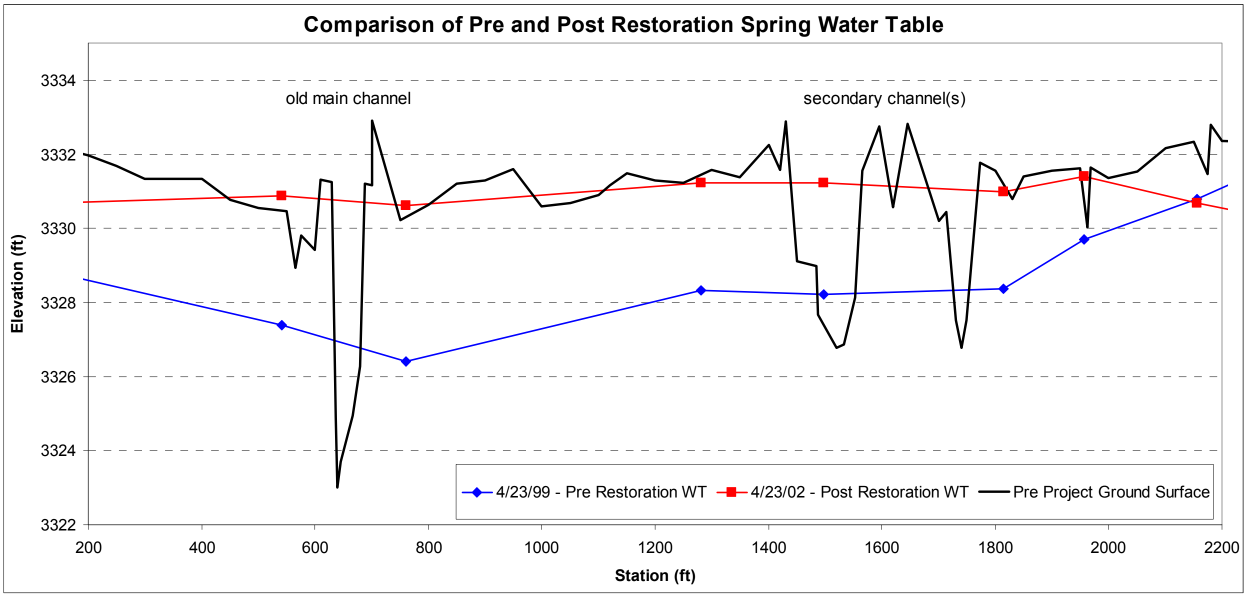

**Figure 8 –** Comparison of pre- (blue line) and post-restoration (red line) water table elevations in late April for ground water transect B. Transect B traverses the valley roughly half way down the meadow. The pre-restoration ground surface is provided to show the locations of old main channel and secondary channels, in addition to allowing the comparison of the restoration's influence on the depth to the water table. Note that the pre-restoration water table slopes toward the old main channel, as it acted as a drain for the meadow's ground water.

**Figure 9 –** A selection of native wildflowers found in the meadow. Clockwise from top left *Mimulus tricolor* (tri-colored monkey flower), *Camassia quamash* (camas), *Sisyrinchium bellum* (blue-eyed grass), *Iris missouriensis* (western blue flag) with butterfly (Photos: Chris Hammersmark).

# A framework for understanding the hydroecology of impacted wet meadows in the Sierra Nevada and Cascade Ranges, California, USA

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**Abstract** Meadows of the Sierra Nevada and Cascade mountains of California, USA, support diverse and highly productive wet-meadow vegetation dominated by sedges, rushes, grasses, and other herbaceous species. These groundwater–dependent ecosystems rely on the persistence of a shallow water table throughout the dry summer. Case studies of Bear Creek, Last Chance, and Tuolumne meadow ecosystems are used to create a conceptual framework describing groundwater–ecosystem connections in this environment. The water requirements for wet-meadow vegetation at each site are represented as a water-table-depth hydrograph; however, these hydrographs were found to vary among sites. Causes of this variation include (1) differences in soil texture, which govern capillary effects and availability of vadose water and (2) elevation-controlled differences in climate that affect the phenology of the vegetation. The field observations show that spatial variation of water-table depth exerts strong control on vegetation composition and spatial patterning. Groundwater-flow modeling demonstrates that lower hydraulic-conductivity meadow sediments, higher groundwater-inflow rates, and a higher ratio of lateral to basal-groundwater inflow all encourage the persistence of a high water table and wet-meadow vegetation, particularly at the margin of the meadow, even in cases with moderate stream incision.

**Keywords** Ecohydrology · Groundwater dependent ecosystem · USA · Water table · Wetland

Received: 31 January 2008 / Accepted: 1 October 2008

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## Introduction

Wet meadows are productive and diverse ecosystems that are common in the Sierra Nevada and Cascade ranges of California, USA. The health of these ecosystems is inextricably linked to the shallow groundwater flowing beneath the meadow (Ratliff 1985). The Sierra Nevada and Cascade foothills begin at ~300 m elevation, and peaks rise to over 4,000 m elevation, resulting in a wide range of climates and ecological communities. Most precipitation falls between November and March, primarily as snow at elevations above 1,500 m. There are strong gradients in annual average precipitation, which range from ~20 to 200 cm due to topography-induced, orographic effects, with higher precipitation totals occurring on the western slope as well as a gradient of increasing precipitation from south to north.

Because little precipitation occurs during the warm and dry summer, wet-meadow vegetation relies on shallow groundwater during the growing season. For this reason, wet meadows are classified as groundwater-dependent ecosystems (Boulton 2005; Murray et al. 2003). The source of the groundwater can be local infiltration and recharge in the meadow, watershed scale groundwater discharge to the meadow, or recharge from a stream to the meadow. Identification of the groundwater source is

DOI 10.1007/s10040-008-0380-4

critical to understanding hydroecologic function and groundwater controls on vegetation patterning, yet heterogeneity and transient conditions within the groundwater flow system can make this determination difficult (Carter 1986; Hunt et al. 1996, 1999; Owen 1995). Extensive monitoring of the water-table configuration (Cooper et al. 2006; Patterson and Cooper 2007; Hammersmark et al. 2008; Loheide and Gorelick 2007) and natural geochemical and isotopic-tracer techniques (Rains and Mount 2002; Atekwana and Richardson 2004; Hunt et al. 1997, 1998; Huth et al. 2004; Matheney and Gerla 1996; Komor 1994) have proven effective for identifying the source of water feeding riparian ecosystems.

Meadows throughout the Sierra Nevada and Cascade Ranges of California have experienced important changes in vegetation and hydrology since the 1850s when European settlers first began to use the land for mining, ranching, and logging. In general, these activities altered hydrologic patterns and processes of ecosystems, either inadvertently or intentionally, often resulting in a lower water table. Because of the tight connection between the vegetation and the groundwater systems, the lowering of the water table typically results in a shift from native wet-meadow vegetation to more xeric vegetation. Four common anthropogenic mechanisms for these ecohydrologic shifts are logging, road and railroad construction, ditching/channelization, and overgrazing (SNEP 1996; Trimble and Mendel 1995; Belsky et al. 1999; Clary and Webster 1990). It is important to recognize that natural changes to the meadow hydrologic regime (Germanoski and Miller 2004; Wakabayashi and Sawyer 2001) and changes to the climatic regime may also cause shifts in vegetation composition and patterning.

Vegetation changes alter the functioning of the meadow and may further change the meadow hydrologic regime. The causes and effects of these ecosystem changes have been described for individual sites (Cooper et al. 2006; Loheide and Gorelick 2005, 2006, 2007; Patterson and Cooper 2007; Hammersmark et al. 2008; Hammersmark 2008), but a comparison of these studies raises several important questions.

First, Hammersmark (2008), Loheide and Gorelick (2007), and Cooper et al. (2006) all present water-table hydrographs associated with wet-meadow vegetation, showing that wet-meadow vegetation is highly correlated with a shallow water table in the Sierra Nevada and Cascade mountains. Yet, comparison of these hydrographs does not reveal a single threshold vegetation hydrograph that could be used to predict the presence or absence of wet-meadow vegetation at all three sites. What is the cause of this apparent difference in water requirements?

Second, Loheide and Gorelick (2007) note strong longitudinal vegetation patterning associated with stream incision; however, this phenomena was observed at neither the site investigated by Cooper et al. (2006) nor that investigated by Hammersmark (2008). What differences in process might help reconcile these conflicting observations?

The purpose of this article is to synthesize the results of case studies of three wet-meadow complexes in the Sierra Nevada and Cascade mountain ranges, Bear Creek, Last Chance watershed, and Tuolumne Meadows (Fig. 1), to answer these questions and identify hydroecological processes that are consistent among meadows as well as those that differentiate meadow function across geographic, geologic, elevation, climatic, and land-use gradients. Using examples from these case studies, the following will be discussed: (1) the linkages between wetland vegetation and the groundwater system, (2) the watershed scale drivers of meadow hydroecology, (3) the drivers of meadow hydroecology within meadow systems, and (4) the implications of ecosystem-groundwater interactions on restoration/rehabilitation planning and efficacy as called for by Bernhardt et al. (2005), Palmer and Bernhardt (2006), and the US Department of Agriculture (USDA 2001).

In this article, the focus is on the water requirements of wet-meadow groundwater-dependent ecosystems and the development of a conceptual framework for understanding the physical processes and conditions necessary to support these ecosystems. This conceptual framework allows one to interpret apparent inconsistencies as well as commonalities in the form and function of meadow systems. This provides a scientific basis for land managers and restoration practitioners who need to understand how processes at unstudied meadows might relate to findings from intensely monitored research sites elsewhere in the region.

## Study site descriptions

### Bear Creek Meadow

Bear Creek Meadow is a low-gradient alluvial floodplain situated at the bottom of the 218 km$^2$ Bear Creek watershed (Table 1). Located at the northwestern margin of the Fall River Valley near the intersection of the Modoc Plateau and the Cascade Range, the meadow is 2.3 km$^2$ in size, at 1,010 m elevation. The Fall River Valley is fed by large springs discharging from permeable volcanic rocks (Meinzer 1927; Grose 1996; Rose et al. 1996) and is underlain by fine-grained lacustrine deposits with hydrologically important clay lenses in the meadow that are overlain by 0.5–2 m of deltaic sands and gravels and 1–3 m of floodplain silty loam soils (Grose 1996; NRCS 2003). The local climate is semi-arid; the meadow receives annual average precipitation of 510 mm mostly as rainfall, while higher elevation areas receive higher precipitation totals largely as snow.

Hydrologic inputs to the meadow include intermittent surface-water inflow from Bear Creek, perennial spring discharge from the Fall River springs, precipitation, and seasonal shallow subsurface recharge from an adjacent irrigated pasture. The Fall River spring system is fed by precipitation, which falls on the Medicine Lake Highlands, perches on low-permeability lacustrine deposits, flows south through fractured basalt and discharges at the downstream end of the meadow (Rose et al. 1996), and forms the headwaters of the Fall River and several short perennial tributaries.

Prior to rehabilitation, Bear Creek Meadow's channels were degraded due to channelization and heavy utilization

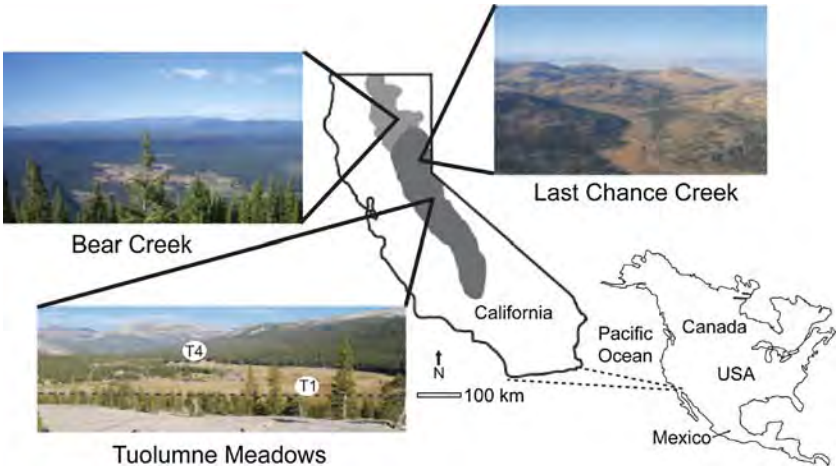

**Fig. 1** Map showing sites and location of Sierra Nevada (*dark grey*) and Cascade ranges (*light grey*) within California, USA, as well as photos of the meadow systems discussed in the text. Labels *T1* and *T4* show the location of transects discussed in the text

as livestock pasture (Spencer and Ksander 2002, Table 1). By the mid 1990s, Bear Creek's main channel had incised and widened to the extent that it was completely disconnected from its floodplain in all but the largest flood events. This channel degradation led to a lowered water table and a conversion of wet and moist meadow vegetation dominated by *Carex nebrascensis*, *Carex athrostachya, Juncus balticus, Juncus covillei* and *Juncus nevadensis* to annual grasses more typical of upland environments, for example *Poa bulbosa, Bromus tectorum* and *Bromus japonicus*.

The meadow was rehabilitated in 1999 using a "pond-and-plug" meadow re-watering strategy, where incised stream channels were intermittently filled with plugs of locally derived alluvial material, and the unfilled, incised channel segments were left as ponds. The new 3.6-km channel was constructed, using remnant channels where possible, with a meandering riffle-pool morphology (Rosgen 1996, 1997; Benoit and Wilcox 1997) with reduced width, depth, and cross-sectional area (Poore 2003). The average depth at riffles was reduced from 2.69 m to 0.89 m, and average bankfull capacity was reduced from 61.7 to 5.35 $m^3$/s (Hammersmark et al. 2008), resulting in more frequent bankfull conditions. These modifications resulted in substantial changes to the meadow hydrologic regime, including: (1) higher groundwater levels and volume of subsurface storage, (2) increased frequency of floodplain inundation and decreased magnitude of flood peaks, (3) decreased baseflow and annual runoff; and (4) increased evapotranspiration

**Table 1** Comparison of hydrologic characteristics of study sites

| | Bear Creek | Last Chance | Tuolumne |
|---|---|---|---|
| Elevation (m asl) | 1,010 | 1,680–1,820 | 2,600 |
| Watershed area ($km^2$) | 218 | 250 | 186 |
| Study site size | 2.3 $km^2$ | ~21 km length of continuous meadow system | 1.6 $km^2$ |
| Precipitation (mm) | 510 | 410 | 1,000 |
| Meadow sediment texture | Silty-clayey loam soil (1–3 m) above sand and gravel layer (0.5–2 m) overlaying lacustrine sediments of the Fall River Valley | Predominantly silts and minor sand and gravel | Sand and gravel |
| Bedrock geology | Fractured basalt with low-permeability lacustrine deposits underlying the Fall River Valley | (1) Tertiary volcanics: rhyolitic flows including some ash and tuff beds, (2) Miocene pyroclastic deposits consisting of andesitic mudflows, breccias, conglomerate and tuffs and (3) Mesozoic granite (Durrell 1987; Lydon et al. 1960) | Predominately granite, with complex fractures near Soda Springs; lateral glacial moraines along valley |
| Extent and cause of degradation | Severe channelization and straightening for agricultural reclamation (1960s); three decades of heavy grazing (Spencer and Ksander 2002) | Severe incision due to logging and grazing; local effects of road and railroad construction | Moderate channel widening due to extensive sheep grazing during the late 1800s |
| Restoration/ rehabilitation | Pond-and-plug | Pond-and-plug and check dam | None |

(Hammersmark et al. 2008). The presence of wet-meadow vegetation was favored by rehabilitation practices because the mean spring and summer depth to the water table was decreased by 1.20 and 0.34 m, respectively, because the water table rose above pre-rehabilitation levels.

### Last Chance Watershed, Plumas National Forest

Last Chance Watershed (250 km$^2$) is located in the Feather River Basin on the eastern slope of the Sierra Nevada in the rain shadow of the mountain crest at an elevation of 1,680–2,350 m (Table 1). It is located in a semiarid environment with mean annual precipitation of 410 mm. Most precipitation occurs as snow during the winter with runoff and recharge occurring during spring snowmelt. The bedrock of the study area contains volcanic flows, pyroclastic deposits, and granitics described in Table 1 and mapped in Fig. 2 (Durrell 1987; Lydon et al. 1960). Given these lithologies, the hydraulic conductivity (*K*) of the granite bedrock is likely much less than that of the Miocene pyroclastics; the Tertiary rhyolites likely have a *K* value intermediate to these two lithologies (Freeze and Cherry 1979). The riparian floodplains consist of silty Quaternary alluvial and lacustrine deposits and collectively form one of the longest continuous meadow systems in the Sierra Nevada.

Wet meadows are classified as groundwater-dependent ecosystems because of their reliance on shallow groundwater during the dry summer growing season. However, stream incision, primarily from grazing, logging, and road and railroad construction, has lowered the water table resulting in aridification of soils in portions of the meadows. In the Last Chance watershed, a reduction in water availability caused a succession from native wet-meadow vegetation to xeric vegetation (Wilcox 2005; Loheide and Gorelick 2005, 2007). Because of extensive restoration efforts, the Last Chance study area has been designated as a demonstration watershed, in which pond-and-plug and check dam rehabilitation sites exist (FRCRM 2004). Pond-and-plug rehabilitation, as described earlier, involves the filling in of incised gullies with sediment excavated for ponds alongside the stream, and check dam rehabilitation includes the installation of low profile drop structures that assist grade control, raise stream water levels, and create small aquatic scour pools on incised streams.

Stream incision results in lowering of the water table and sagebrush (*Artemisia tridentata*) encroachment, which has important hydrological and biogeochemical consequences (Berlow et al. 2002; Elmore et al. 2003; Houghton et al. 1999; Schimel et al. 2001). Woody shrubs can modify streamflow, runoff, recharge, and the ratio of plant transpiration to total evapotranspiration due to changes in evaporative leaf area, volume of root systems and the duration of physiological activity (Huxman et al. 2005). Loheide and Gorelick (2005) have used forward-looking infrared thermal imagery to map and quantify restoration/rehabilitation-induced changes in evapotranspiration at this site using an evapotranspiration-mapping algorithm (ETMA; Loheide and Gorelick 2005). ETMA provides evapotranspiration estimates of 1.5–4 mm/day for xeric dry land grasses and 5–6.5 mm/day for wet-meadow vegetation (Loheide and Gorelick 2005). Stream incision induces vegetative changes, decreases evapotranspiration rates, and alters the balance of meadow hydrologic processes. Loheide and Gorelick (2007) formalized the linkages between the hydrologic and vegetation changes with a coupled groundwater-vegetation model in an archetypical meadow, based on characteristics of meadows in the Last Chance watershed, which predicted the development and widening of observed swaths of xeric vegetation near channels as the depth of incision increased.

### Tuolumne Meadows, Yosemite National Park

Tuolumne Meadows in Yosemite National Park is one of the largest high-elevation meadows in the Sierra Nevada. The meadow is located at 2,600 m elevation and has a drainage area of 186 km$^2$, with a mean annual precipitation of 1,000 mm (Table 1). The basin is largely composed of granitic rocks, with metavolcanics on the east. Lower elevations are blanketed with glacial till, which serve as important local groundwater aquifers. The soils of the basin are thin, rocky, and have limited water storage capacity.

Tuolumne Meadows was heavily used as summer pasture for thousands of sheep and cattle each year in the late 1800s, which appears to have resulted in damage to the vegetation. This type of utilization and impact occurred throughout the southern Sierra Nevada (Ernst 1949; Dull 1999). One of the most apparent issues in the meadow today is the invasion of lodgepole pine (*Pinus contorta*), a species that occurs primarily in upland forests. Tree invasion into meadows has been a well researched topic in the Sierra Nevada, Cascade Range and Rocky Mountains in the western US (Vale 1981a, b; Vankat and Major 1978; Millar and Woolfenden 1999; Cunha 1992; Franklin and Mitchell 1967; Patten 1963; Vale 1978). Tree invasion has been blamed on hydrologic changes due to road construction and dewatering, climate change, and heavy livestock grazing which disrupted the meadow sod (Cunha 1992). Cooper et al. (2006) focused on analyzing Tuolumne Meadows to determine what hydrologic factors have influenced the meadow vegetation, and the data collected during that study as well as during the summer of 2007 are discussed here.

## Methods

### Field methods: water-table depth and vegetation classification

At Bear Creek Meadow, Last Chance watershed, and Tuolumne Meadows, 28, 44, and 73 hand-augered monitoring wells, respectively, were installed across the meadow to characterize water-table depth and its influence on vegetation patterns. At all three sites, some wells were

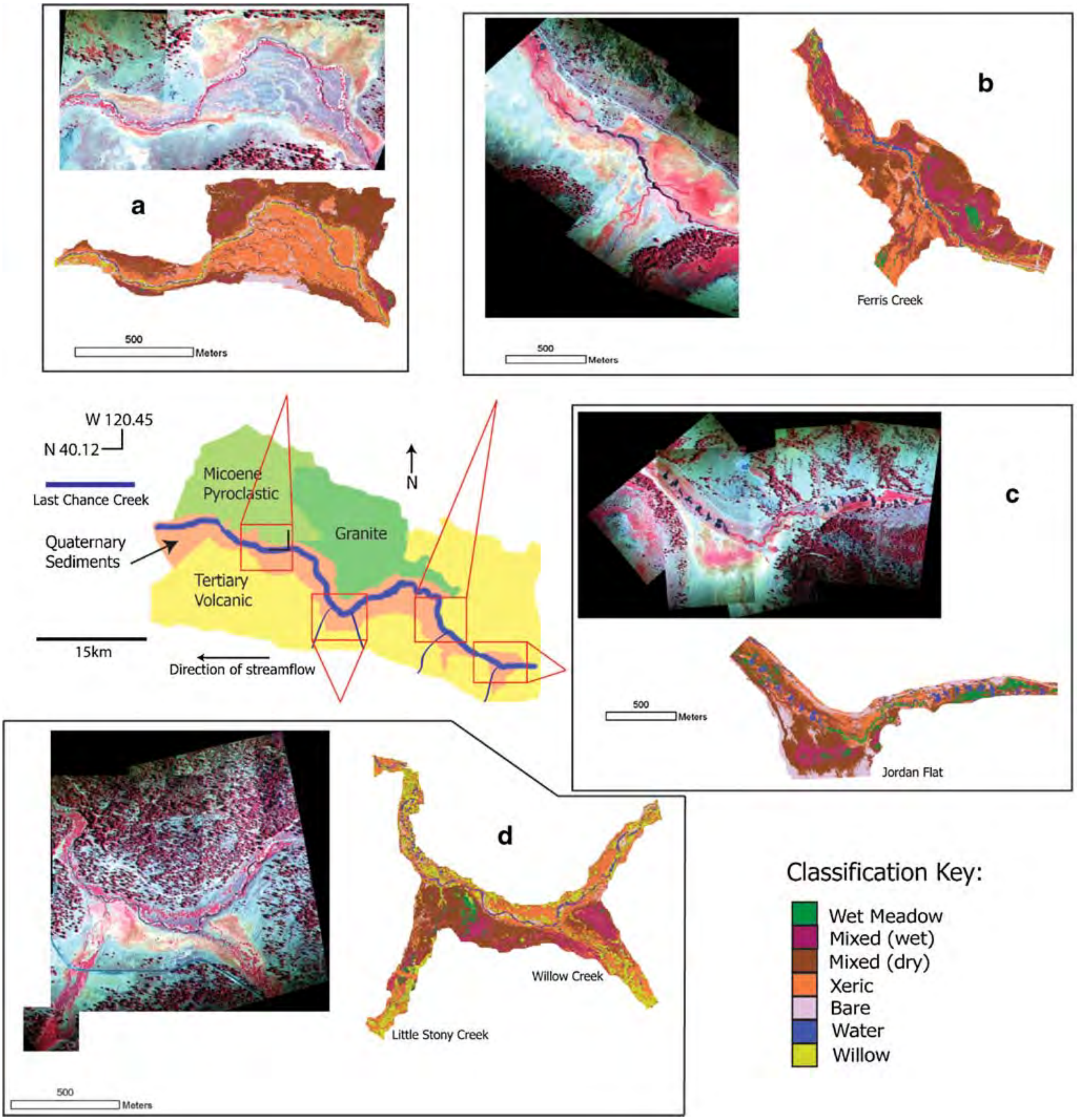

**Fig. 2** Geologic map (*center left*) showing location of paired color infrared mosaics (*images*) and vegetation classification *(maps of meadows only*) at four meadows along Last Chance Creek. **a** Asymmetric vegetation patterning with wet-meadow vegetation to the north of the channel and xeric vegetation and abandoned stream channels to the south. **b** Effects of check-dam rehabilitation efforts showing large expanse of dominantly wet-meadow community nearly two decades after project completion. **c** Effects of pond-and-plug rehabilitation efforts with wet meadow and mixed vegetation appearing near the ponds only 1 year after project completion. **d** Wet-meadow vegetation supported by groundwater funneled through the Willow Creek and Little Stony Creek tributary meadows

equipped with continuously recording pressure transducers while others were measured by hand approximately every two weeks during the summer months. At Bear Creek, Hammersmark (2008) sampled vegetation in 128 plots, each 4 m$^2$, distributed along 15 transects, and used two way indicator species analysis (TWINSPAN; Hill 1979; McCune and Mefford 1999), to classify the herbaceous vegetation of the restored meadow. In Tuolumne Meadows, a vegetation plot 20 m$^2$ in area centered on each well was used to characterize vegetation composition and coverage by species. Vegetation was classified using TWINSPAN (Gauch 1982). In the Last Chance watershed, Loheide and Gorelick (2007) collected vegetation data in 1-m$^2$ plots centered on each well and classified these data into four groups ranging from wet meadow to xeric upland. These data were not originally collected for this cross-site comparison, and further discussion of portions of the data sets can be found in Hammersmark et al. (2008), Hammersmark et al. (2008), Loheide and Gorelick (2007), and Cooper et al. (2006).

## Remote sensing methods

For this study, color infrared (CIR) imagery was used to map vegetation in the Last Chance watershed and to determine the hydroecologic processes that led to the observed vegetation patterning. CIR imagery of Last Chance Creek was collected from a helicopter in August 2005 using a RedLake MS4100 multi-spectral camera collecting red, green, and near infrared wavelengths. CIR imagery is valuable for identifying vegetation because healthy, mesic vegetation reflects near infrared electromagnetic radiation to a much greater extent then xeric communities.

CIR data were exported to image processing software (ENVI 4.4) for analysis. 88 CIR images were geo-referenced to a digital orthoquadrangle of the Last Chance region and mosaiced. For visualization purposes, the near infrared, red, and blue data are displayed as red, blue, and green, respectively, to produce a false color image. Four example CIR mosaics are displayed in Fig. 2. Maximum likelihood classifications of the four regions of Last Chance were performed using image-processing software to create maps of vegetation cover. Seven regions of interest including open water, bare soil/sand, xeric vegetation, wet-meadow vegetation, mixed-meadow vegetation primarily wet, mixed-meadow vegetation primarily dry, and willows were selected as end members for the maximum likelihood classification. Wet-meadow species in Last Chance include sedges and rushes (e.g. *Carex angustata, Carex douglasii, Carex nebraskensis Juncus balticus*) whereas xeric vegetation communities include sagebrush and dryland grasses (e.g. *Artemisia tridentata, Hordeum jubatum, Poa secunda* ssp. *secunda, Elymus elymoides*). The vegetation classification has only been applied to the meadows for which it is intended, and the surrounding hillslopes are masked out in the classification images. While this classification should be considered qualitative as the vegetation has not been analyzed on the ground, the data clearly show detailed spatial patterns that cannot be obtained using limited point vegetation analysis.

## Analytical and numerical modeling techniques

Meadow aquifers are often fed by groundwater discharge into the meadow system from the hillslopes, which helps to support wet-meadow-vegetation communities (Fig. 3). In order to close the hydrologic budget of the meadow aquifer, the magnitude of the groundwater flux must be accounted for accurately. This water may enter the meadow vertically as a basal flux ($N$) as well as inflow from the hillslope boundary as lateral flow ($Q_x$). Both Loheide and Gorelick (2007) and Hammersmark et al. (2008) have recently performed hydrologic modeling studies on meadows and have accounted for regional groundwater flow to the meadow system with the goal of predicting vegetation patterning. At Bear Creek, Hammersmark et al. (2008) simulated discharge to the meadow predominately as a flux which entered the margin of the meadow. In an archetypical meadow representative of Last Chance watershed meadows, Loheide and Gorelick (2007) simulated regional groundwater flow as a basal flux to the meadow. This paper builds on these studies to discuss how the partitioning of this flux between the vertical discharge through the base of the aquifer and the horizontal discharge through the aquifer margin will affect the configuration of the meadow water table and the associated vegetation patterning.

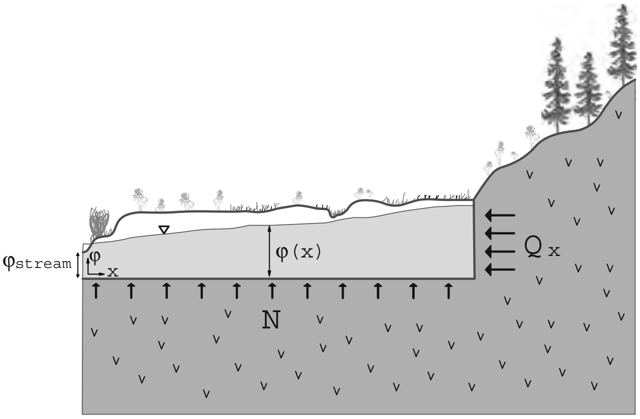

**Fig. 3** Conceptual model of regional groundwater flow to the meadow system, which drains towards the stream if the water level in the stream ($\varphi_{\mathrm{stream}}$) is lower than that in the aquifer. This water may enter the meadow vertically through underlying bedrock as a recharge (or accretion) flux ($N$) as well as from the hillslope boundary as a lateral inflow. The *light grey region* represents the model domain

One-dimensional, unconfined, steady-state groundwater flow in aquifers can be approximated using the Dupuit-Forchheimer assumptions (Bear 1972; Haitjema 1995). Analytical solutions were presented by Bear (1972, 1979) for the two extreme cases in which groundwater discharges to the meadow either uniformly as a basal flux ($N$) or as a lateral flux at the meadow margin ($Q_x$). For this study, both lateral and basal groundwater discharges are significant, and groundwater drains toward the stream with a head of $\varphi_{\mathrm{stream}}$. Thus, the following solution was developed, which describes the distribution of the hydraulic head, $\varphi(x)$, in the meadow aquifer, ($0<x<L$), which has a uniform hydraulic conductivity ($K$):

$$\phi(x) = \sqrt{\phi^2_{stream} - \frac{2Q_x}{K}x + \frac{N}{K}(2L - x)x} \qquad (1)$$

Note, $Q_x$ must have a negative sign to enter the meadow and flow to the left using the coordinate system defined in Fig. 3. If groundwater use by vegetation ($\mathrm{ET_G}$) is to be considered, then $N$ should be replaced by the quantity ($N$-$\mathrm{ET_G}$). It is important to note that the Dupuit-Forchheimer approximation cannot simulate the development of seepage

DOI 10.1007/s10040-008-0380-4

faces, which may result in overprediction of the depth to the water table near the channel using Eq. (1).

Four scenarios, called A, B, C, and D, were considered to assess the relative importance of: (1) a meadow's hydraulic conductivity, (2) the rate of groundwater flow feeding the meadow, and (3) the partitioning of groundwater flow between basal and lateral fluxes on the position of the water table. In all cases, $\varphi_{\mathrm{stream}}$ was set to 2.5 m, and the length of the meadow ($L$) between the stream and the margin was 100 m. In each scenario, an equivalent inflow of water to the meadow was simulated as occurring 100% as a basal flow, 100% as a lateral flow, or a 50/50% mix of basal and lateral flows. In cases A and B, the high hydraulic conductivity cases, $K$ was set to $10^{-3}$ m/s, whereas a value of $10^{-4}$ m/s was used for cases C and D. In cases A and C, the low groundwater inflow cases, the total inflow per unit width of meadow was $5\times10^{-6}$ m$^2$/s. For 100% lateral inflow, $Q_x=5\times10^{-6}$ m$^2$/s and for 100% basal inflow $N=5\times10^{-8}$ m/s. For the high groundwater inflow cases (B and D), these rates were doubled so that the total inflow per unit width of meadow was $1\times10^{-5}$ m$^2$/s.

The magnitude and partitioning of groundwater flow from hillslopes between lateral and basal inflows affects water-table position within the meadow as described by Eq. (1); however, this partitioning is controlled by watershed-scale geologic features, soil hydrologic properties, rainfall and snowmelt rates, and evapotranspiration characteristics of the hillslope vegetation. Two-dimensional, steady-state groundwater flow modeling was used to assess the pattern of discharge to the meadow systems. COMSOL Multiphysics (Comsol 2005), a general purpose finite element modeling environment which has been used for hydrologic applications (e.g. Cardenas and Wilson 2007; Loheide 2008) was used to simulate four cases (I-IV) discussed later. These simulations model a transect from the meadow stream to the ridgetop through the domain illustrated in Fig. 4, which consists of bedrock and meadow sediment subdomains. A constant inflow rate is specified as the upper boundary condition. A head is specified at the location of the stream within the meadow. No flow boundaries are specified at the lateral boundaries beneath the stream and beneath the ridge top based upon symmetry arguments.

## Results and discussion: the groundwater–wet-meadow-vegetation connection

### *Direct use of groundwater by wet-meadow vegetation*

Wet-meadow vegetation relies on shallow groundwater for support throughout the dry summer. Evidence of this dependency and direct use of groundwater by phreatophytes can often be seen as diel water-table fluctuations in detailed water level records collected from wells screened across the water table in environments with a shallow water table (White 1932; Meyboom 1967; Gerla 1992; Loheide et al. 2005; Butler et al. 2007; Loheide 2008). This reliance has been observed as diel water-table fluctuations in meadows alongside Bear Creek and Last Chance Creek (Fig. 5). These records reveal diel water-table fluctuations that show a decline in water-table elevation during the daylight hours, while plant roots extract water from the phreatic zone for transpiration, followed by a recovery period of rising water-table elevation during the night when transpiration is near zero. These water-table fluctuations appear to be a virtually ubiquitous feature when the water table is within the range between the land surface and the maximum rooting depth in wet-meadow ecosystems. If there is ponding on the land surface, water level records are controlled by surface-water processes and generally do not show the typical diel water-table fluctuations, though the pattern can propagate into surface-water flows through the influence this process exerts on surface-water/groundwater interactions (Bond et al. 2002). Conversely, as the water table drops toward the bottom of the root zone, the diurnal fluctuations become

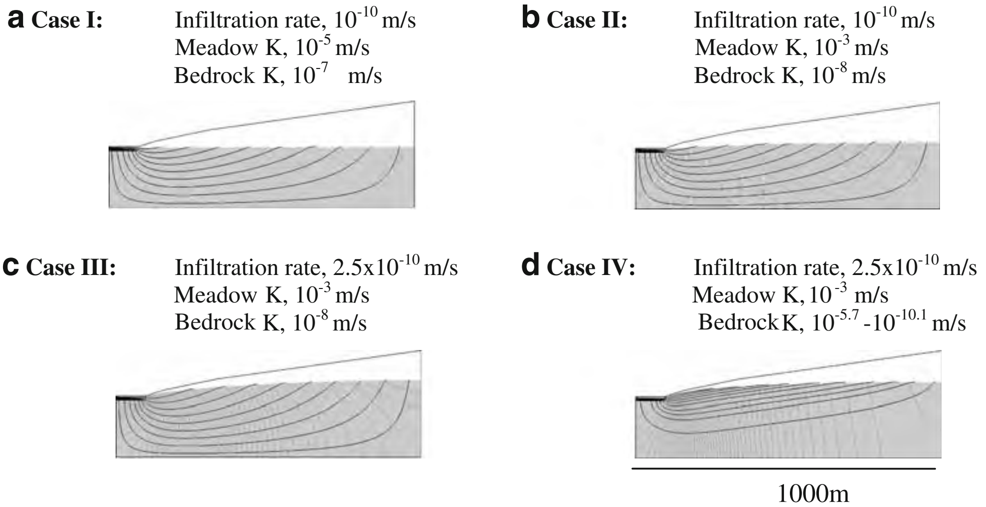

**Fig. 4** Regional groundwater flow to the meadow system represented as a cross-sectional flownet through the watershed with *darker lines* representing flowpaths and *lighter lines* representing equipotentials. Cases *I–IV* are described in the text and illustrate the geologic control of the watershed on the magnitude of groundwater discharging to the meadow as well as the proportion entering as basal and marginal influxes

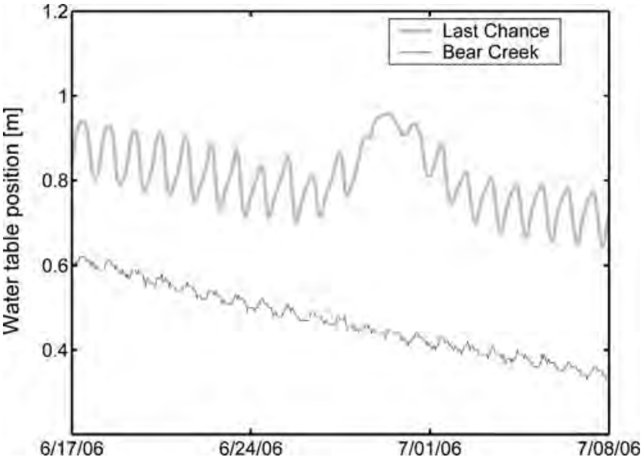

**Fig. 5** Evapotranspiration-induced diel water-table fluctuations which demonstrate the groundwater and ecosystem connection in wet-meadow environments. Water-table position is measured from an arbitrary datum

muted and disappear (Butler et al. 2007; Lott and Hunt 2001). Under these conditions, the vegetation must rely on the limited water available within the vadose zone and may result in early senescence of the vegetation if conditions become too dry.

In Fig. 5, the magnitude of the diel fluctuations differs from site to site. While the amplitude of the fluctuation is indicative of the rate of groundwater consumption (White 1932; Loheide 2008), much of the difference between the sites is due to the water-storage properties of the soil, which is characterized by the readily available specific yield (Meyboom 1967; Gerla 1992; Lott and Hunt 2001; Loheide et al. 2005). Coarse-grained sediments result in smaller observed water-table fluctuations when compared with fine-grained sediments, even for the same root-water uptake rate. This is the primary reason the water-table fluctuations are smaller in the loamy sediment in the vicinity of the observation well at Bear Creek than the large fluctuations observed at the well located in silty sediment of Last Chance watershed. Evapotranspiration (ET)—driven fluctuations were not observed at most sites in Tuolumne Meadows because groundwater fluctuations were dominated by snowmelt-driven stream discharge variations (Lundquist et al. 2005; Loheide, University of Wisconsin, and Lundquist, University of Washington, unpublished data, 2007).

The data in Fig. 5 were recorded for a 3-week period beginning in mid-June 2006. On 27–28 June, cloudy conditions occurred, and a small amount of precipitation was recorded in the Last Chance watershed (less than 4 mm at the two weather stations). These overcast conditions resulted in lower solar radiation, cooler air temperature, and higher humidity, all of which combined to create much lower potential ET rates. In addition, the small amount of water that infiltrated into the soil provided an additional temporary reservoir of water in the vadose zone that was available to the vegetation. Both the lower potential ET and the greater contribution of soil water to the vegetation resulted in much lower vegetative groundwater consumption during these days. This resulted in a slight rise in the water table, which is likely a result of the reduced groundwater component of ET and the complex interactions that occur between the vadose zone, the capillary fringe, and the water table during rain events (Heliotis and DeWitt 1987). This example indicates that diurnal water-table fluctuations result from groundwater use by vegetation, but do not result from vegetative use of vadose water.

## Wet-meadow vegetation communities: observed vegetation patterns in relation to groundwater flow systems

The vegetation classification of Hammersmark (2008) resulted in four community types being identified for Bear

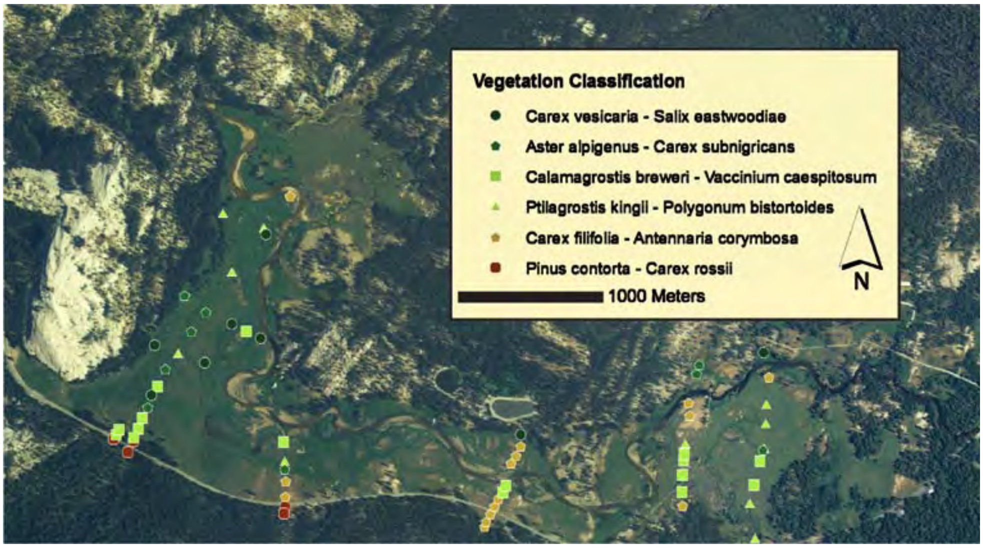

**Fig. 6** Aerial imagery of Tuolumne Meadows showing vegetation composition at well locations. Vegetation patterning does not show strong and persistent longitudinal patterns but rather patches that show relationships with abandoned meander channels. The aerial imagery is courtesy of the USDA National Agriculture Imagery Program (2007)

DOI 10.1007/s10040-008-0380-4

Creek Meadow, which were arranged in three distinct hydrologic groups based on summary hydrologic variables calculated for the growing season (May–August) such as average water-table depth ($\overline{wtd} \pm standard\,deviation$), minimum water-table depth, maximum water-table depth, range of water-table depth, and number of days the water-table depth is within 30 cm of the soil surface. Differences between community means for each variable were tested with analysis of variance and Tukey-Kramer honest significant difference (SAS Institute 2004). The *Poa pratensis-Bromus japonicus* ($\overline{wtd} = 119.4 \pm 44.4cm$) community type was the driest, the *Carex nebrascensis-Juncus balticus* ($\overline{wtd} = 60.3 \pm 12.6cm$) and *Downingia bacigalupii-Psilocarphus brevissimus* ($\overline{wtd} = 58.5 \pm 19.8cm$) community types were intermediate and the *Eleocharis macrostachya-Eleocharis acicularis* ($\overline{wtd}= 18.4\pm 28.0cm$) community type was the wettest (Hammersmark 2008). The distribution of these communities in the meadow is patchy; however some patterns were observed. The *Poa pratensis-Bromus japonicus* community dominated the upper third of the meadow even in plots 2 to 20 m from the stream margin, while in the lower two-thirds of the meadow, this community type was limited to locations >100 m from the stream margin. The *Carex nebrascensis-Juncus balticus* community type was found near the stream in the lower two-thirds of the meadow. The *Downingia bacigalupii-Psilocarphus brevissimus* community type was limited to the bottoms and margins of channels and swales, which were intermittently or seasonally inundated. The *Eleocharis macrostachya-Eleocharis acicularis* community type was limited to depressions on the floodplain, which were inundated in the early growing season. Importantly, there was no clear longitudinal zonation of vegetation communities, except those related to abandoned channels, which are the currently low-lying swales discussed above.

In Tuolumne Meadows, the vegetation analysis resulted in six plant communities. The *Carex vesicaria-Salix eastwoodiae* community occured in oxbows along the Tuloumne River that had seasonal flooding and deep standing water. The *Aster alpigenus-Carex subnigricans*, *Ptilagrostis kingii-Polygonum bistortoides*, and *Calamagrostis breweri-Vaccinium caespitosum* communities are the main herbaceous wet-meadow communities. The *Carex filifolia-Antennaria corymbosa* and *Pinus contorta-Carex rossii* communities are found in uplands within or on the edge of the meadow. The distribution of these communities can be seen in Fig. 6, which shows vegetation composition at the well locations overlain on aerial photography. The imagery does not show clear and persistent longitudinal patterning, but rather shows that the position of abandoned river meanders plays an important role in the vegetation patterning, likely due to differences in both sediment texture and topography.

The relationship between groundwater depth and vegetation patterning can be understood by comparing vegetation along water-table transects. For example, the *Carex vesicaria* dominated community occurred in depressions along transect 1 (e.g. 800–850 m in Fig. 7a). The upland communities were located near the road between 0 and 100 m distance along this transect, where the depth to the water table is the greatest. From 100 to 1,000-m distance along the transect, level meadow areas were dominated by the *Aster alpigenus-Carex subnigricans* community, while communities dominated by *Ptilagrostis kingii* and *Calamagrostis breweri* occurred on raised surfaces that had slightly deeper summer water tables.

Several water sources supply Tuolumne Meadows: the Tuolumne River supplied by its entire watershed, small tributary streams from sub-watersheds, and groundwater from local hillslope aquifers. Along transect 1 (Fig. 7a), vegetation in the region from 800 m to the river is hydrologically connected to and supported by the river. The region between 0 and 800 m is supported by groundwater from local hillslope moraines and bedrock, and the groundwater flow direction is toward the river.

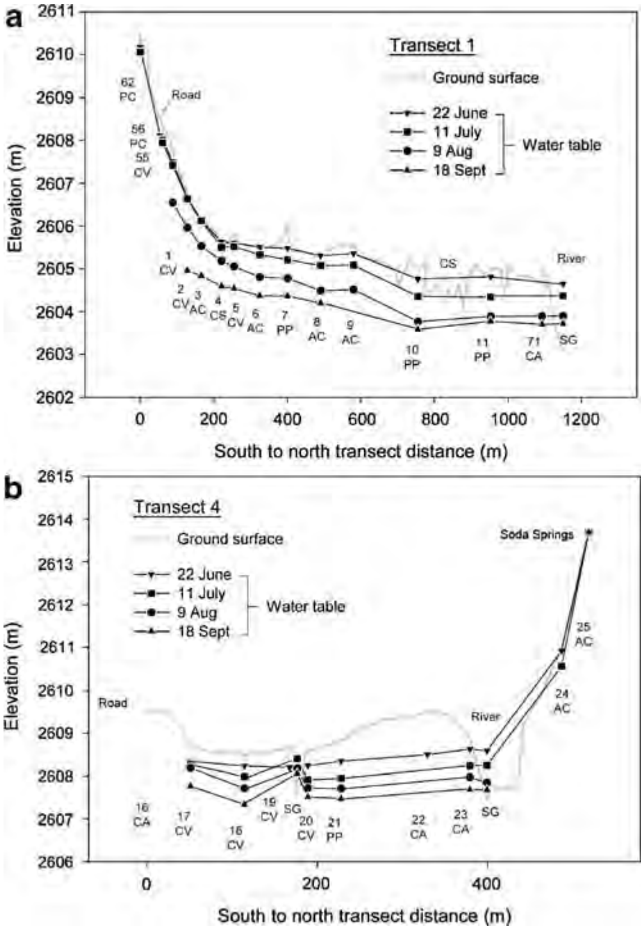

**Fig. 7** Groundwater measurements on four dates in 2006 for water level and vegetation monitoring transects **a** T1 and **b** T4 shown on the photograph of Tuolumne Meadows in Fig. 1. The *letters beneath the well numbers* indicate the vegetation composition as follows: *Carex vesicaria-Salix eastwoodiae* (*CS*), *Aster alpigenus-Carex subnigricans* (*AC*), *Ptilagrostis kingii-Polygonum bistortoides* (*PP*), *Calamagrostis breweri-Vaccinium caespitosum* (*CV*), *Carex filifolia-Antennaria corymbosa* (*CA*) and *Pinus contorta-Carex rossii* (*PC*). Modified from Cooper et al. (2006)

Groundwater supports most areas within Tuolumne Meadows, and the four wet-meadow community types dominated by *Carex vesicaria, Aster alpigenus, Ptilagrostis kingii*, and *Calamagrostis breweri*, occupy different landscape positions and landforms where suitable summer water-table depths occur. Inundation and saturation to the surface persists longest in *Carex vesicaria* dominated areas and for shorter periods in the *Aster alpigenus, Ptilagrostis kingii*, and *Calamagrostis breweri* dominated areas.

Figure 2 shows a geologic map of the Last Chance watershed with paired CIR and vegetation classification at four sites (Fig. 2a–d). The vegetation classification grades from wet-meadow communities dominated by sedges and rushes to xeric vegetation communities dominated by dryland grasses and sagebrush. The typical vegetation pattern observed in meadows with incised channels in Last Chance watershed was described by Loheide and Gorelick (2007), and consists of xeric vegetation in approximately symmetric swaths around incised channels and more mesic and hydric vegetation toward the meadow margin. Figure 2 shows sites that deviate from that strongly longitudinal and symmetric vegetation pattern. Figure 2a shows a highly asymmetric vegetation pattern with a narrow swath of xeric vegetation adjacent to an incised channel to the north which grades into a mesic vegetation community. This is in contrast with a very extensive region of xeric vegetation with only narrow strips of mesic vegetation in remnant channels and at the meadow margin to the south of the channel. Figure 2d shows xeric vegetation to the north of Last Chance Creek and wet-meadow vegetation to the south where two tributaries join Last Chance Creek. Figure 2b and c show the effects of check dam and pond-and-plug rehabilitation, respectively. These vegetation patterns will be used as examples to help illustrate meadow hydroecologic function in the following sections.

## Water requirements of wet-meadow communities

The presence of ET induced water-table fluctuations discussed in the previous section indicates groundwater consumption by transpiring plants, and the near ubiquity of these fluctuations in wet meadows indicates that wet-meadow vegetation relies on a shallow water table in the Sierra Nevada and Cascade ranges. Many authors, who have presented this water requirement as either a time-invariant threshold depth to the water table or as a threshold water-table hydrograph that varies through the growing season, have shown that water-table depth is highly correlated with vegetation community type in wet-meadow systems, indicating that local hydrology is the most important factor determining vegetation community type and distribution (Allen-Diaz 1991; Stromberg et al. 1996; Castelli et al. 2000; Darrouzet-Nardi et al. 2006; Dwire et al. 2004; Hammersmark 2008; Kluse and Allen Diaz 2005; Loheide and Gorelick 2007; Martin and Chambers 2001 and 2002; McKinstry et al. 2004; Patterson and Cooper 2007; Sala and Nowak 1997; Steed and DeWald 2003). While water availability is likely the primary driver of this observed relationship, the underlying physiological reason for this correlation may also be related to drivers associated with water-table position such as soil redox potential (Dwire et al. 2006), thermal influences on biotic processes (Ratliff and Harding 1993), soil moisture (Stringham et al. 2001), and pedological development and soil chemistry (Chambers et al. 1999). However, it is also important to note that more than one plant community type might exist under the same physical conditions, but one community type prevails simply because it established first at the exclusion of the other community type.

Because strong relationships between water-table depth and vegetation type have been observed in many wet-meadows, Allen-Diaz (1991) noted the potential for predicting changes in vegetation patterning and composition based on water-table configuration. Loheide and Gorelick (2007) and Hammersmark et al. (2008) have pursued this approach based on water requirements they determined specifically for their meadow systems, while Rains et al. (2004), Springer et al. (1999), and Baird et al. (2005) have pioneered the approach in other riparian environments. Henszey et al. (2004) found that for the riparian grasslands in Nebraska, mean growing season water-table depth is not the most important predictor of vegetation type, but rather short-term high water level metrics such as the 7-day moving average water level high and the 10% cumulative frequency curve, were more influential in determining vegetation type.

In the Sierra Nevada and Cascade Ranges, riparian water-table hydrographs follow a very regular pattern: first, the hydrographs reach a maximum elevation, most often at the land surface during the peak of snowmelt, which may be maintained for several weeks to months. Then the water-table drops as meadow groundwater drains to streams and plants consume water. The period of high water, the rate of water-table decline, and the ultimate depth of water at the end of the growing season (ie., total range of water-table depth) all influence the type of vegetation found at a site. The persistence of wet-meadow vegetation is constrained by two hydrologic features: (1) the early-growing season moisture conditions must be sufficiently wet to cause waterlogged and anaerobic conditions which wet-meadow vegetation can tolerate but is inhospitable to competing upland vegetation communities and (2) sufficient moisture must remain during the late-growing season to support plant growth and reproduction. Like Henszey et al. (2004), Hammersmark (2008) found that mean water-table depth was not the most robust predictor of species presence, but rather minimum (shallowest) water-table depth and the number of days that the water table was within 30 cm of the soil surface were the summary variables most strongly correlated with the different communities. Because of the strong seasonality of climate in the region, all of these features can be captured in a vegetation threshold hydrograph approach as proposed by Loheide and Gorelick (2007). These thresholds describe the maximum water-table depth required by a vegetation community as it varies throughout the growing season. They are determined empirically, by obtaining the water-table depth hydrographs from several wells located in a given vegetation community for representative years (typically at least one wet year and one dry year). This threshold can then provide an envelope of groundwater hydrographs which are suitable for a given vegetation type. A similar red-yellow-green water-table regime suitability approach has been proposed by the Environment Agency in the UK (Wheeler et al. 2004). While these threshold approaches appear to provide a robust prediction of vegetation community at sites where extensive data are available, little is known about the transferability of these water requirement relationships from site to site. The effectiveness of these threshold approaches, as well as hydrologic metrics used to determine jurisdictional wetlands, is dependent on their ability to characterize whether the extent and duration of the hydrologic wet period is aligned with the growing season. A framework is proposed which may be useful for predicting how elevation, which corresponds to growing season length, and soil texture, which controls capillary rise, may affect wet-meadow water requirements. On average, phenologic stages of wet-meadow vegetation (Ratliff 1983) are reached later in the year at higher elevations, due to later snow melt and cooler temperatures. Even though there is a delay in the onset of the growing season associated with cooler temperatures at higher elevations, a high water table is still required during the early portion of the growing season because it makes conditions undesirable for competing upland plants. In addition, shallow groundwater may need to persist until mid-summer to nurture wet-meadow vegetation through the critical reproductive stages in a low elevation meadow, whereas similar vegetation at high elevation exposed to similar soil and nutrient conditions may require shallow groundwater through late-summer. This elevation variation in water requirements is represented schematically in Fig. 8a as a shift to the right for a conceptual vegetation threshold hydrograph (Loheide and Gorelick 2007) that is expected for a wet-meadow community at increasingly higher elevation.

The late-season portion of the vegetation threshold hydrograph required to support wet-meadow vegetation also varies from site to site because of differences in soil texture and the resulting capillary rise. Fine-grained soils have a larger capillary fringe, resulting in larger volumes of soil water above the water table, much of which may be accessible to plants even though the water table itself is below the root zone. There are two sources from which plants can extract water under these conditions. First, they may deplete the finite volume of water stored in the vadose zone directly. Second, by extracting this water, they lower the matric potential in the vadose zone and create an upward gradient which drives water flow from the water table into the vadose/root zone above. These capillary effects tend to be greater in finer-grained soils with low values of α and β in the Van Genutchen (1980) model of soil water retention (Carsel and Parrish 1988).

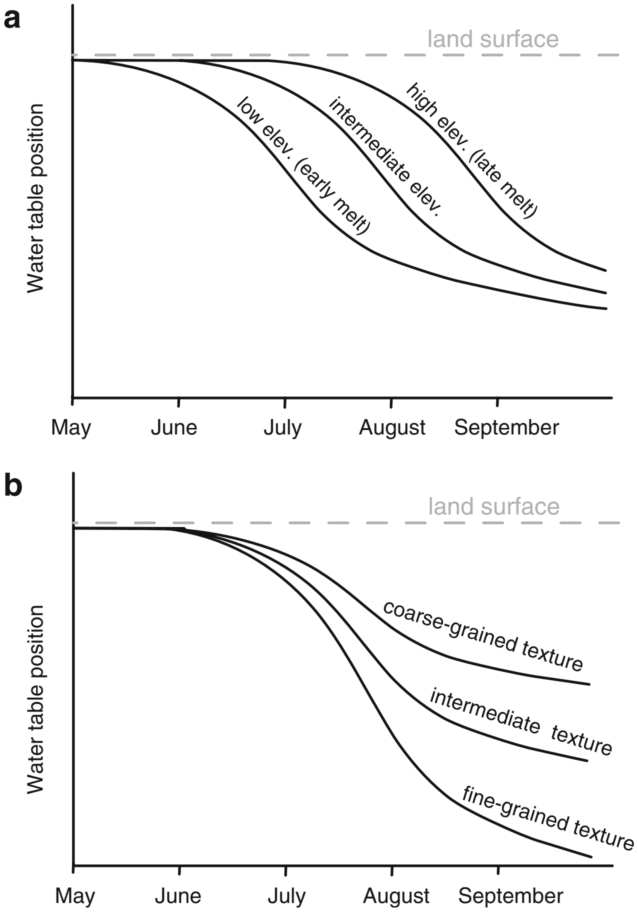

**Fig. 8** Proposed shifts in the vegetation threshold hydrograph required to support a wet-meadow vegetation community at **a** different elevations and **b** in soils of various textures

For these two reasons, loamy and silty soils have more available water in the vadose zone just above the water table, and can support wet-meadow vegetation with a slightly deeper water table. This effect on the vegetation threshold hydrograph is depicted conceptually in Fig. 8b as a downward extension of the vegetation threshold hydrograph as soil texture fines from sands and gravels to silt sized-particles. None of the study sites had clay soils, which do not typically support meadow vegetation in the Sierra Nevada and Cascade Ranges, so this soil type was not considered. Figure 9 shows multi-year average water-table hydrographs collected from shallow wells sited within wet-meadow communities from the three study areas. The hydrograph for Last Chance watershed represents the mean of water level records from 2004 and 2005 from seven wells in wet-meadow vegetation plots based on data from Loheide and Gorelick (2007). The hydrograph for Bear Creek represents the mean of simulated water level records from 2004–2006 for 47 plots in the *Carex nebrascensis-Juncus balticus* wet-meadow community from Hammersmark (2008). The hydrograph for Tuolumne Meadows represents the mean of eight water level records from wells sited in the *Aster alpigenus-Carex subnigricans* wet-meadow community type for 2006 and 2007.

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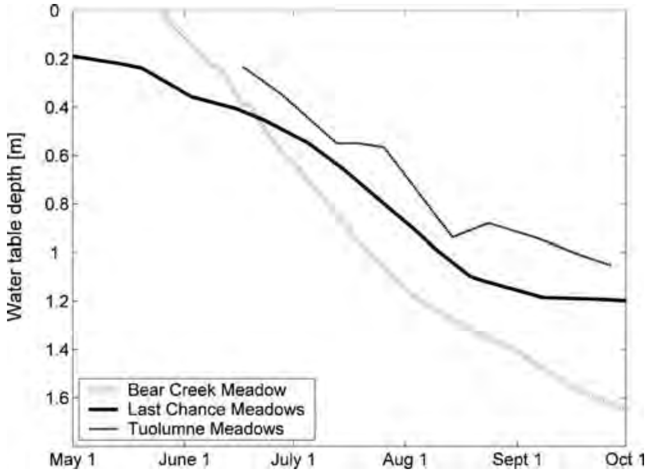

**Fig. 9** Observed mean water-table depth hydrograph (multi-year average) for sedge and rush dominated wet-meadow communities at Bear Creek, Last Chance, and Tuolumne Meadows

While the observations are limited, they appear to be consistent with the predicted effects of soil texture and elevation on vegetation threshold hydrographs. First, Fig. 9 shows a general shift to a higher water table at later dates (shift to the right) as elevation increases from Bear Creek, to Last Chance, to Tuolumne Meadows. Second, the shallowest late season water-table depths are found at the site with the coarsest soil, Tuolumne Meadows. Bear Creek, with silty-clayey loam soils, has the deepest mean hydrograph, and Last Chance, with predominantly silts, has an intermediate hydrograph, even though a large soil textural difference is not evident between the sites. It is unclear whether the slightly higher clay content at Bear Creek could account for the downward stretching of the water-table hydrograph that was observed.

To support the hypothesized elevational and sedimentological effects on the vegetation threshold hydrograph, additional data and study are required. First, the mean observed hydrograph for a vegetation community is not the vegetation threshold hydrograph for the community. The actual water-table depth observed at a site could be substantially higher than the minimum, or threshold, required for that vegetation community. Second, the records available from only three sites over 2- to 3-year periods are not sufficient to determine the long-term average water-table hydrographs given the large interannual climatic variability of the Sierra Nevada and Cascade ranges. Although the interannual variability of water-table depth and timing is large, each of the study sites included data from at least one water year (2004 and 2007) ranked among the driest quartile, with earliest snowmelt, within the past 90 years, and at least one year (2005 and 2006) ranked among the wettest quartile, with latest snowmelt, within the past 90 years, based on 90-year records from the Merced River at Happy Isles, which are highly correlated with California-wide snowpack characteristics (Peterson et al. 2000). Thus, while the durations of observations were short, they do sample the known variability in regional climate.

Despite these caveats, the limited comparisons made in Fig. 9 indicate that the hypotheses proposed in Fig. 8 may provide a useful framework for transferring vegetation threshold hydrographs between sites. Predicting these vegetation threshold hydrographs at degraded sites where original data cannot be collected is critical to designing restoration/rehabilitation projects that will meet the water requirements of desired vegetation. Further evaluation of this framework in controlled greenhouse studies where sufficient replicates can be performed and true thresholds can be assessed is required to validate these hypotheses.

## Modeling insights on geologic controls of groundwater discharge to meadows: implications for vegetation patterning

While groundwater flow in meadows is transient, responding to seasonal patterns and hydrologic events, several generalizations can be made from the steady-state analysis presented here. Results from the analytic model described by Eq. (1) are presented for the four cases (A–D) considered in Fig. 10. As demonstrated by Haitjema and Mitchell-Bruker (2005), the water table does not always mimic surface topography. Figure 10a and b show that if the hydraulic conductivity is large relative to the groundwater inflow rate (cases A and B), the resultant water table is very flat. Because the water table is flat, spatial patterns in the depth to the water table (land elevation minus water-table elevation) are controlled by topographic variability rather than the subtle water-table gradient. The ecohydrologic consequence of this is that vegetation patterning, which can be predicted with depth to the water table, is topographically controlled.

High hydraulic-conductivity meadow sediment and relatively gradual hydraulic gradients exist at Tuolumne Meadows and Bear Creek, as horizontal transport is controlled by lower sand and gravel layers. Figure 7b shows the topography and water level measurements along a transect crossing the Tuolumne River in Tuolumne Meadows. Sites 17, 18, 19, 20 along this transect are dominated by *Calamagrostis breweri* and *Vaccinium caespitosum* (Cooper et al. 2006), a vegetation community which is characteristic of wet meadows (Ratliff 1982), whereas site 21 is vegetated with a grassland community which has high canopy coverage of *Ptilagrostis kingii*, *Danthonia intermedia*, and *Antennaria corymbosa*. The higher ground between site 21 and 23 is occupied by a xeric (dry meadow) community which is dominated by *Artemisia tridentata* and also includes *Carex filifolia*, *Antennaria corymbosa*, *Muhlenbergia filiformis* and *Solidago multiradiata*. On the opposite side of the river, groundwater levels are controlled by discharge associated with Soda Springs, and *Aster alpigenus, Muhlenbergia filiformis*, *Dodecatheon alpinum*, and *Juncus balticus* are the dominant species present at Soda Springs. Because of the high hydraulic conductivity of the sands and gravels in this portion of Tuolumne Meadows, the water table perpendicular to the Tuolumne River is relatively flat.

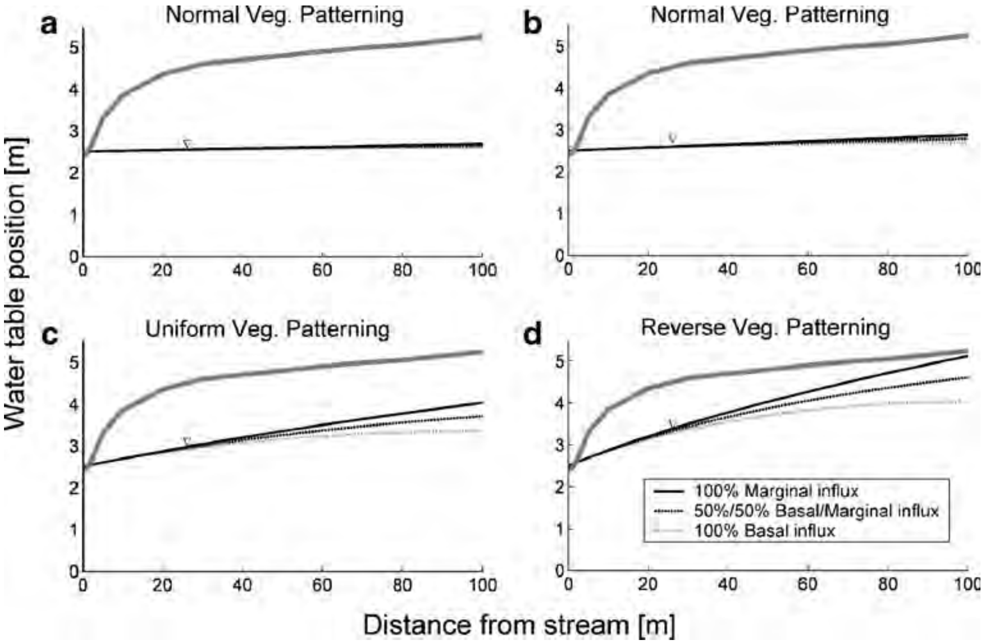

**Fig. 10** Water-table position as predicted by the steady state model represented by Eq. (1) for the case with a stream with a stage of 2.5 m at the left side of the domain ($x$=0 m) and a meadow margin at the right side of the domain ($x$=100 m). **a** and **b** represent cases A and B, respectively, with sediments of high hydraulic conductivity ($K$=$10^{-3}$ m/s), whereas **c** and **d**, cases C and D, respectively, represent meadows with sediments of lower hydraulic conductivity ($K$=$10^{-4}$ m/s). **a** and **c** represent cases with lower groundwater inflow, whereas *the right two panels* represent cases with higher groundwater inflow to the meadow. Although the lines in **a** and **b** overlap, *each panel shows three lines* representing the inflow as completely a basal influx, as completely a marginal influx, and as a mixed influx

The topographic high near the stream creates a greater depth to the water table and results in a drier vegetation community in this region.

Similarly, local topographic features are very important to the resulting mosaic of vegetation distribution. Remnant channels/swales are common at Bear Creek, Tuolumne Meadows, and Last Chance watershed such as those seen to the south of the stream in Fig. 2a, through Tuolumne Meadows in Fig. 6, and between 780 and 880 m in Fig. 7a. These depressions provide locations with shallower depth to groundwater, and thus favor hydric, and in some cases vernal pool, species assemblages.

On the other hand, meadows with sediments of lower hydraulic conductivity (cases C and D) relative to regional groundwater discharge to the meadow result in water tables that slope strongly toward incised stream channels (Fig. 10c and d). If the topography of the meadow is relatively flat, then the water-table position, which is related to distance from the stream as shown by Eq. (1), is the primary determinate of water-table depth and vegetation patterning. As demonstrated by Loheide and Gorelick (2007) for an archeotype meadow, this is clearly the case in silty sediments such as those found in the Last Chance watershed. As illustrated in Fig. 10, when the water table slopes strongly toward the incised channel (because the stream is incised and the hydraulic conductivity is low), the greatest depth to the water table occurs just outside of the incised meander belt, resulting in a swath of xeric vegetation near the channel, whereas more mesic and hydric vegetation occurs near the margin of the meadow. This distinctive vegetation patterning caused by stream incision resulting in swaths of meadow degradation is shown in Fig. 2a and d as well as in Loheide and Gorelick (2007). While this pattern is typically somewhat symmetrical on both sides of the incised channel, Fig. 2a shows a highly asymmetric case where a very wide swath covering almost the entire meadow exists to the south of the deeply incised channel (~3 m), whereas a very narrow xeric swath quickly transitions to mixed mesic vegetation to the north. A large difference in hydraulic conductivity of the meadow sediments (higher to the south) could result in the flatter and deeper water table which is inferred to the south; however, there is no evidence that the sediments differ on opposite sides of the channel. Rather, a major geologic contact between relatively high-$K$ Miocene-aged pyroclastics and lower-$K$, Tertiary-aged, rhyolitic volcanics occurs beneath the meadow shown in Fig. 2a. This geologic difference results in greater groundwater discharge from the northern hillslopes resulting in a higher water table and a wetter vegetation community on the north side of the channel compared with the meadow to the south. Comparison of Fig. 10c and d shows that even a factor of two increase in groundwater discharge to the meadow can appreciably raise the water table in the meadow, particularly near the margin (~1 m increase).

Elsewhere along Last Chance Creek, a contrast in vegetation community types can be seen on opposite sides of the meadow in Fig. 2d. The north side of the meadow is bounded by a granitic hillslope with very low hydraulic conductivity and little groundwater discharge. As a result, groundwater in the meadow drains nearly completely to the deeply incised channel, and xeric vegetation dominates. On the south side, the forested hillslopes have developed on Tertiary volcanics. While these rocks did not result in high groundwater discharge to the meadow in Fig. 2a, this geologic unit is the source of all perennial streams within the watershed.

These valleys, whether perennial or ephemeral, convey groundwater toward the main stem channel. Thermal remote sensing similar to that presented by Loheide and Gorelick (2006) identified groundwater discharge to the main stem of Last Chance from several of these tributary meadows (unpublished data). Remote-sensing-based vegetative analysis of the Last Chance watershed indicates that no fewer than nine tributary meadows with wet-meadow vegetation funnel groundwater from the regions of the watershed with Tertiary volcanic bedrock. Examples are Doyle Crossing (Loheide and Gorelick 2005), Jordan Flat (shown in Fig. 2c) and the confluences of Little Stony Creek (ephemeral) and Willow Creek (perennial) to Last Chance (shown in Fig. 2d). These tributaries result in a large lateral influx (large $Q_x$ in Fig. 3) into the main-stem meadow, which supports a high water table and wet-meadow vegetation, as well as supplying baseflow to the main stem channel even during times when there is no surface contribution.

The example of tributary groundwater contributions to main stem meadows is a clear example of lateral groundwater inflow, but regional groundwater flow can also reach the meadow as a basal flux. Loheide and Gorelick (2007) assumed that basal groundwater inflow was the primary inflow of groundwater to the meadow and estimated the magnitude of this flux based on measured vertical hydraulic gradients and estimates of sediment hydraulic conductivity. On the other hand, Hammersmark et al. (2008) determined that groundwater flow to Bear Creek Meadow occurred as lateral flow from an adjacent irrigated area along a portion of the meadow margin. Similarly, as reported by Patterson and Cooper (2007), shallow lateral groundwater flow at Drakesbad Meadow in Lassen Volcanic National Park (California) was the primary source of groundwater inflow and was disrupted by road conditions.

The authors recognize that the end member cases of only basal or lateral inflow may not be common, and it may be more typical that a meadow will receive water from a combination of both sources. The model presented in Eq. (1) is able to provide insight into how partitioning of groundwater inflow between basal and lateral fluxes affects water-table position. Plots a–d of Fig. 10 illustrate the difference in water-table position for each of the four cases. In all cases, lateral inflow results in a higher water-table position at the meadow margin than an equivalent inflow of water distributed as a uniform basal flux. This result occurs because the flux at all locations is $Q_x$ in the lateral inflow case, whereas the flow decreases from $N \times L$ to 0 from $x=0$ to $x=L$ in the case of a basal flux, as the discharge to the meadow occurs uniformly between the channel and the meadow margin. Because the flux goes toward zero as $x$ increases in the basal inflow case, the gradient required to move water through the meadow aquifer toward the stream is less than that of the lateral inflow case at all positions greater than $x=0$, and in fact, the hydraulic gradient goes to zero at $x=L$ in the basal inflow case. Because the lateral inflow results in a higher water table near the meadow margin, lateral inflow is more likely to result in wet-meadow vegetation than an equal amount of basal inflow.

Four scenarios were used to determine the effects of inflow rates and bedrock and meadow hydraulic conductivity values on the distribution of groundwater discharge to meadows. The results and parameters for these scenarios are given in Fig. 4. In case I, a low inflow rate and a high bedrock $K$ value was simulated as a base case. This simulation showed that while the majority (~70%) of discharge to the meadow occurred through the base of the meadow, a non-negligible portion of groundwater also entered the meadow horizontally at the meadow bedrock interface.

In case II, the same inflow rate was simulated as in case I, but both a higher meadow hydraulic conductivity and lower bedrock hydraulic conductivity was simulated. While the contrast between meadow and bedrock conductivity changes by three orders of magnitude in a way that encourages more groundwater discharge to the margin of the meadow, the difference is less than 10% and would not be a primary factor in most geologic settings.

In case III, the same values of bedrock and meadow hydraulic conductivity are simulated, but the inflow rate is increased by a factor of 2.5. While this change causes a 150% increase in groundwater discharge to the meadow, it has very little effect on the partitioning of groundwater inflow to the meadow between the lateral and basal fluxes.

In case IV, the same inflow rate and meadow hydraulic conductivity is simulated, but a hydraulic conductivity of the bedrock decreases from $10^{-5.7}$ m/s at the top point of the cross section shown in Fig. 4 to $10^{-10.1}$ m/s at the base. This decrease is based on a linear decrease of the log of the hydraulic conductivity and is intended to represent a decrease in hydraulic conductivity with depth often observed when fracture aperture decreases due to the increasing pressure with depth. In this case, most of the groundwater flow to the meadow is lateral flow rather than a basal flux. At Bear Creek, a decrease in hydraulic conductivity with depth occurs as the lacustrine sediments are encountered and likely encourages a greater percentage of the discharge to enter the meadow as a lateral, rather than basal, flux. This analysis shows that under reasonable geologic conditions, either lateral or basal groundwater inflow may dominate even in watersheds with relatively uniform geology.

The analysis above assumes relatively homogenous geologic characteristics. However, in most watersheds of the Sierra Nevada and Cascades, geologic heterogeneity and locations of fractures and faults also play a considerable role in determining groundwater flow paths and the distribution of groundwater discharge areas. In fact, mesic and hydric vegetation communities, often associated with springs and surrounded by more xeric vegetation, are the primary indication of the location of these discharge areas.

Springs and associated vegetation of this type are found at each of the three sites considered. For example, springs at Bear Creek Meadow support areas dominated by the *Carex nebrascensis*–*Juncus balticus* wet-meadow community. In the Last Chance watershed, discharge areas such as these exist on slightly raised topography relative to the surrounding xeric meadow and supports small patches (~3 m diameter) of willows, sedges, and rushes. At Tuolumne Meadows in Yosemite, Soda Springs supports wet-meadow vegetation as discussed earlier and shown in Fig. 7b.

## Management and restoration implications and conclusions

Every meadow in the Sierra Nevada and Cascade ranges is unique, and no research site will provide a perfect analogue to guide land managers and restoration practitioners in understanding the hydroecology of a specific site. The purpose of this paper has been to use three intensively studied meadows to describe the general hydroecology of meadow systems and suggest a framework that might help to explain (1) how vegetation water requirements vary along elevational and soil textural gradients and (2) how hydrogeologic characteristics influence the groundwater flow system and vegetation patterning of a meadow.

Wet-meadow vegetation patterning and ecology is tightly linked to hydrologic patterns and processes in the Sierra Nevada and Cascade ranges (Allen-Diaz 1991; Castelli et al. 2000; Darrouzet-Nardi et al. 2006; Dwire et al. 2004; Hammersmark 2008; Kluse and Allen Diaz 2005; Loheide and Gorelick 2007; Martin and Chambers 2001, 2002; McKinstry et al. 2004; Patterson and Cooper 2007; Sala and Nowak 1997; Steed and DeWald 2003). The high seasonality of precipitation in this environment results in the driest portion of the year corresponding with the summer growing season, when vegetation water consumption is greatest. Wet meadows form where a shallow water table during the summer fulfills the water requirements of this groundwater-dependent ecosystem.

Humans have disrupted the hydrologic regime of these ecosystems both intentionally through channelization, stream straightening, drainage efforts, and culvert construction and unintentionally through feedbacks associated with grazing, logging, road and railroad construction, and anthropogenic climate change. These hydrologic alterations have resulted in unanticipated vegetation changes and degraded ecosystem function throughout the meadow systems of the region. All of these commonly cited mechanisms of meadow degradation have one thing in common-each alters the hydrology of the meadow in a way that lowers the water table and triggers a succession to xeric plant species. These altered meadows have insufficient duration of soil saturation within the root zone of plants to be classified as jurisdictional wetlands, under the Clean Water Act (Environmental Laboratory 1987). In addition, the drying of surface soils leads to altered vegetation composition, and meadows can be dominated by plants which are not typical of wetlands. Thus, many former wetland communities would fail to meet the three parameters required to be considered jurisdictional wetlands, and they would not be regulated by the US government. However, restoration would reverse this process, and many restored and rehabilitated meadows would once again meet the jurisdictional requirements for wetlands.

A critical feature of any restoration or rehabilitation effort must involve restoring the hydrologic processes that allow the existence and persistence of a shallow water table throughout the growing season. Both pond-and-plug and check-dam rehabilitation efforts have proven effective in raising the water table and encouraging reestablishment of wet-meadow vegetation as shown in Fig. 2b and c, respectively, although other methods that attempt true restoration may be more suitable in other areas.

The vegetation threshold hydrograph is a simple method for quantifying and visualizing the water requirements of wet-meadow vegetation communities as they vary with time through the growing season. The best technique for determining these water requirements is to monitor water levels on-site or in nearby meadows for several years to determine the range of suitable groundwater regimes for the vegetation community of interest, in the same watershed, at a similar elevation, with similar soil and nutrient conditions. Unfortunately, there are rarely available resources to follow this approach, and the best alternative is to use the most appropriate data available in the literature.

It appears that these vegetation hydrographs should be shifted upward for sites with coarser textured soils and downward for sites with finer textured soils to account for differences in capillarity compared to a reference site. In addition, it is suggested that the vegetation threshold hydrographs should be shifted to the left for lower elevation sites and to the right for higher elevation sites when compared to the reference site. While this paper does not provide a quantitative measure of the magnitude of these shifts, it does provide a useful conceptual framework for understanding how and why a vegetation threshold hydrograph at one site may differ from that at another location.

The steady-state analytical model developed here is not intended to predict water-table elevation within a specific meadow at a specific time, as these systems experience transient conditions, which, as evidenced by the vegetation threshold hydrographs, are an important determinant of vegetation composition. However, this model could be used as a screening tool to compare processes among sites. It is obvious that, if all other things are equal, meadows receiving higher groundwater inflow will have a higher water table and be more likely to support wet-meadow vegetation. In addition, the hydraulic conductivity of the meadow sediments ranges over orders of magnitude and is important in determining the drainage to the stream in meadow systems. Sites with low hydraulic conductivity are more likely to have steeper groundwater gradients toward the stream, resulting in longitudinal vegetation patterning with a deeper water table and xeric vegetation near the channel and a shallow water table and mesic or hydric vegetation near the meadow margin. Lastly, this model shows that marginal groundwater inflow raises the water table near the margin of the meadow more than an equivalent basal flux feeding the meadow.

Land-managers and restoration practitioners should work to include both of these groundwater inflow processes in their conceptual and physical models of meadow function. Numerical modeling indicates that for watersheds with relatively uniform bedrock hydraulic conductivity, a good rule of thumb is that approximately 70% of the regional groundwater flow entering a meadow occurs as basal flux; however, this value will be reduced if the hydraulic conductivity of the bedrock decreases with depth. Though interflow through soil layers was not considered here, this process could also increase the percentage of water feeding the meadow at the meadow margin.

To understand observed hydroecologic changes, predict future trends, and implement restoration or rehabilitation efforts to prevent or reverse ecosystem degradation in meadow systems (Wright and Chambers 2002; Klein et al. 2007; Loheide and Gorelick 2007; Hammersmark 2008), it is imperative to: (1) quantify the water requirements of wet-meadow vegetation communities, and (2) identify the inflows of water to the meadow and to understand the physical and geologic controls on these processes. The framework presented here identified elevation and edaphic gradients as the primary variables for understanding how vegetation water requirements are expected to differ among sites. The rate and distribution of regional groundwater flow feeding a meadow system, the degree of stream incision, and the hydraulic properties of the meadow sediment are identified as the primary factors influencing groundwater flow in a particular meadow. Recognition of how these factors differ among meadow systems and the effect they have on meadow hydroecology provides resource managers and restoration practitioners with a means for transferring results from reference sites that have been more intensively studied to systems in which they are working.

**Acknowledgements** The current work was primarily supported by the National Science Foundation under grant No. CBET-0729838; however, research at all the sites has been ongoing and has been supported by grants from the National Science Foundation under grant No. EAR-0337393, the National Park Service, University of California-Center for Water Resources (grant No. WR995), USDA US Geologic Survey (grant No. 06HQGR0074), the David and Lucile Packard Foundation (grant No. 2001–16376), University of California-John Muir Institute of the Environment-Environmental Fellows Program, the Cantara Trust, and the Peter and Nora Stent Fund at the Peninsula Community Foundation. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the funding agencies. We would like to thank those who contributed to the extensive data collection and/or analysis including: J. Mount, M. Rains, S. Gorelick, A. Abeles, C. Avila, B. Ebel, C. Heppner, E.-L. Hinckley, N. Martin, K. Moffett, K. Rockett, M. Ronayne, B. Loheide, B. Mirus, J. Sydnor, S. Violette, E. Booth, J. Baccei, F. Lott, J. Roche, B. Huggett, H. Roop, A. Wickland, M. Bibbo, and D. Grauer. Finally, we would like to thank the reviewers of this manuscript for their helpful comments and suggestions, which improved the quality of this article.

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# Restoring California's Wild Watersheds

*Why more water for wildlife means more water for people.*

Restoring the Wild

WHY MORE WATER FOR WILDLIFE MEANS MORE WATER FOR PEOPLE

**Jane Braxton Little** *posted May 27, 2010*

Jim Wilcox is sitting on a rock near a quarter-acre pond watching a pair of willow flycatchers flit in and out of the brush across the water. The 15-inch rainbow trout he spied a week ago does not flash on this summer morning, but Wilcox knows it's down there somewhere beneath the surface.

He allows himself a small smile. Three years ago his pond-side perch was in the middle of a sagebrush field high in the headwaters of California's Feather River, 170 miles northeast of Sacramento. Red Clover Creek trickled through in a braided network of rutted gullies.

A century of logging, road-building, and intensive overgrazing had reduced this and other meadows throughout the Sierra Nevada to baked and barren flats. Today the stream meanders through a meadow lush with native grasses and small ponds.

Jim Wilcox is among those who have worked for 25 years to improve the land and water that runs through the Feather River watershed.

Photo by Jane Braxton Little

Wilcox, a former logger, is part of a 25-year effort to restore all of the meadows within the upper Feather River basin, an area larger than Delaware. As program manager for the Feather River Coordinated Resource Management group, he works with ranchers, timber owners, anglers, and federal and state agency officials—anyone who shares an interest in improving the land and the water that cascades down to the Sacramento Valley and the delta that empties into San Francisco Bay. At a time when climate change is putting unprecedented pressure on water supplies, these mountain meadows may be a first step in preserving both the environment and the economy. Restoring them helps revitalize the watershed and wildlife, and it also helps sustain the downstream farms, ranches, towns, and cities that depend on the alpine water.

Water, after all, delivers most of the effects of global warming: melting icebergs, rising sea levels, lower stream flows, reduced snowpacks, and increased tropical storms. Throughout the American West, communities, cities, and entire state economies have relied on mountain snowpacks, which replenish the streams that feed water supplies. Now, as climate change is altering historic snowfall patterns, land managers are turning to meadows to help reduce the effects of a warming planet.

## Nature's Reservoirs

Mountain meadows store water, acting as natural reservoirs that hold back floodwaters. By slowing the heavy spring flows and releasing them gradually over the dry summer months, healthy watersheds can increase the quantity of water available downstream.

In California, where agriculture is the economic mainstay, the impacts of climate change could be devastating. The Sierra Nevada snowpack supplies two-thirds of the state's water needs. The Sierra's 22 major river systems nourish farms and orchards in California's Central Valley, which produces

8 percent of the nation's crops. Over the last century, however, late spring runoff has declined 25 percent. Scientists predict even more dramatic reductions over the next 90 years, as global warming restricts snowfall to the highest elevations. The timing of peak snowmelt throughout the range is already earlier and could occur a full two weeks sooner by the end of the century, according to climate scientists.


The restored Red Clover Creek.

Photo by Jane Braxton Little

Scientists and land managers are launching innovative plans to maximize the storage capacity of meadows throughout the Sierras, which stretch 400 miles along the state border with Nevada. The most ambitious project involves nearly 300,000 acres of floodplains, an area about 20 times the size of Manhattan. The National Fish and Wildlife Foundation, a Washington, D.C.-based nonprofit created by Congress, is providing $15 million and coordination for work in as many as 20 Sierra Nevada watersheds over the next 10 years. Along with restoring fish and wildlife habitat, their goal is to continue delivering fresh water to the rest of the state.

"Everyone agrees that California will have less snow and more rain in coming decades. There is no doubt that water is the crisis here and now," says Timothy Male, the foundation's director of wildlife and habitat conservation.

The diminishing snowpack is likely to provoke more skirmishes in the statewide water wars that pit the north against the south, farmers against environmentalists, and rural interests against urban. The underlying problem is a demand for water that has outgrown today's supplies, U.S. Interior Secretary Ken Salazar told *The Los Angeles Times*. California, he said, is "sitting on a ticking time bomb, and you better get your act together, because otherwise the bomb's going to go off."

## Making Up for Lost Snowpack

The Feather River watershed lies at the northern end of the Sierra range among its lower peaks. The impacts of diminishing snowpacks will take their toll here first, says Wilcox, who has lived in these mountains since the 1970s. The effects on the quantity and timing of the downstream flow will be dramatic, he says. That puts even more pressure on restoring meadows in the watershed that provides more than 5 percent of California's freshwater supply.

Wilcox wasn't thinking about climate change when he began working with the Feather River alliance 25 years ago. The group's focus was on the erosion that was choking the river. Instead of conventional dredging of reservoirs and riverbeds, a handful of local entrepreneurs decided to try reducing the sediment buildup where it began: upstream in the tributary creeks and meadows.

In 1985, just before winter closed the roads, they built four small U-shaped rock and gravel dams in Red Clover Creek, 60 miles above a series of hydroelectric dams owned by Pacific Gas & Electric Company. The dams were designed to slow the water flow and trap in-stream sediment. That winter tested the experiment. The 20 inches of rain that fell in five days washed out century-old bridges and roads. To nearly everyone's surprise, the dams not only survived; they also held back their share of sediment.

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## page 2

Emboldened by that success, the small coalition of county officials and businessmen expanded to include ranchers, environmentalists, and state and federal officials. Although many of them had been at odds over land management issues, they realized they could only heal the watershed if they cooperated. Wilcox had been a firsthand witness to stream dredging and other practices harmful to ranchlands and forests. A man more at home in a pickup truck than an office, he was eager to be a part of reversing the damage. "I believe in watershed restoration. It has always been in my bones," he says. And that became the Feather River coalition's goal: restoring entire meadows along with the creeks flowing through them.

**Now, as climate change is altering historic snowfall patterns, land managers are turning to meadows to help reduce the effects of a warming planet.**

Among the methods they have pioneered is a low-tech procedure known as "pond and plug." Crews with heavy equipment dig several of the channels wider and deeper, creating small ponds. They use the excavated dirt to fill the remaining gullies back to the original ground level. Along Red Clover Creek, the groundwater began rising almost immediately after the crews finished plugging the channels. By the following spring the ponds were flush with the water that would otherwise have raced downstream in late winter. Above and below the pond where Wilcox sits, the creek has found its way across the meadow in a natural, meandering channel.

The Feather River group has completed 66 restoration projects, which include 3,900 acres of meadow and

44 miles of stream. Since the work began, the data from a series of permanent monitoring stations show that the flow out of restored meadows is greater and lasts longer into the summer. Water temperatures have dropped despite an increase in average air temperatures, and stream turbidity, a measure of the amount of dirt and debris suspended in the water, has decreased to almost half pre-project levels. Groundwater, which never reached the surface before the restoration work, is now consistently at or above ground level for at least part of the year.

## From Water to Wildlife

The Feather River projects have inspired the much larger Sierra-wide meadow restoration coordinated by the National Fish and Wildlife Foundation. Private landowners, universities, local and national resource organizations, and the U.S. Forest Service are working together to design strategies that will raise the water table and slow the flow out of mountain meadows. In an area from the Pit River in the north to the Kern River in the south, they are evaluating potential projects to determine which will yield the maximum benefits to fish and wildlife and the greatest quantities of water. Their goal is to restore at least 20,000 acres a year by 2014, says Male.

“Nationwide, we’re looking for tangible actions that address the realities of climate change. This is one of the best examples in America of a restoration initiative that can directly help people and wildlife adapt to our changing planet,” Male says.

**Leave it to Beavers?**

Nature's water engineers can restore river channels.

The plan, over the first five years, calls for restoring 60,000 acres of meadow. As the water table rises and meadows soak up more water from melting snows, native habitat lost for decades should return. Among the endangered species expected to benefit are the yellow warbler, Yosemite toad, Lahontan cutthroat and golden trout, Townsend’s big-eared bat, and the Sierra Nevada red fox.

But the effects of widespread meadow restoration will also flow downstream to farmers and other water users. The Forest Service manages about half of the Sierra’s degraded meadowlands. The agency is determining which of the 11,700 separate meadows in 10 national forests need to be restored. All are located on streams important for water supply, says Barry Hill, a regional hydrologist. Using foundation funds, the Forest Service hopes to determine the amount of additional water available for downstream use once the meadows return to health.

The Sierra projects are unique among large-scale water restoration efforts in the United States because of their potential to increase the amount of water available in a river system, says Male. Comprehensive efforts to restore the Chesapeake Bay, the nation’s largest estuary, focus on improving the quality of water flows throughout the 64,000-square-mile region. In the

Everglades, a wide-ranging plan to revive a dying ecosystem aims to improve the distribution of flows throughout 18,000 square miles in southern Florida. Along the lower Mississippi River and coastal Louisiana, the largest wetlands restoration effort is designed to reverse the pattern of land erosion by buffering against floods and hurricanes and, like all of the major projects, improving wildlife habitat.

Just how much more water healthy Sierra Nevada meadows can deliver is a matter of debate. Some scientists believe the boosts in stream flow may be absorbed by increases in vegetation in the new, restoration-created habitats. Others believe restoration could contribute up to 6.5 billion gallons of additional water storage throughout the California range. Over time, says Male, these restored meadows could hold 16 to 160 billion gallons of fresh water. That's equal to the size of one of the new dams state officials have proposed for construction to offset the state's declining snowpack.

Restoring mountain meadows will not solve California's water crisis. That will take a collective commitment from the agriculture industry, from municipalities, and from everyone who depends on the Sierra snowmelt for their livelihoods and their lives. It will also require more political will than elected officials have traditionally marshaled. Wilcox believes the public recognizes the value of healthy watersheds. He is optimistic that stream restoration will become routine as more people understand its importance upstream and downstream.

Meanwhile, the benefits to wildlife are unequivocal. In the wet meadow surrounding Red Clover Creek, the number of waterfowl species has doubled since Wilcox and his crews completed the pond-and-plug project. He has seen buffleheads, gadwalls, and two species of teal breeding in early spring. Sandhill cranes, willow flycatchers and 10 other species on state and federal watch lists have returned to the area. Walking through Red Clover Valley from the pond, Wilcox bends down to study a clump of dancing hairgrass, one of a handful of plant types that have regenerated from seeds dormant in the soil for decades. He has yet to see elk but he has found their tracks—the first in the area in decades.

### Interested?

- , a conservation organization based in Washington, D.C., focuses on protecting rivers, wildlife, and water supply and quality. The organization's Web site also contains information about meadow restoration in California.
- The nonprofit provides grants to conservation projects across the United States.
- To find out more about the Feather River project, visit the .

*Jane Braxton Little wrote this article for Water Solutions, the Summer 2010 issue of YES! Magazine. Jane covers natural resource issues from California's northern Sierra Nevada. Her work has appeared in Scientific American, Nature Conservancy, and Audubon, where she is a contributing editor.*

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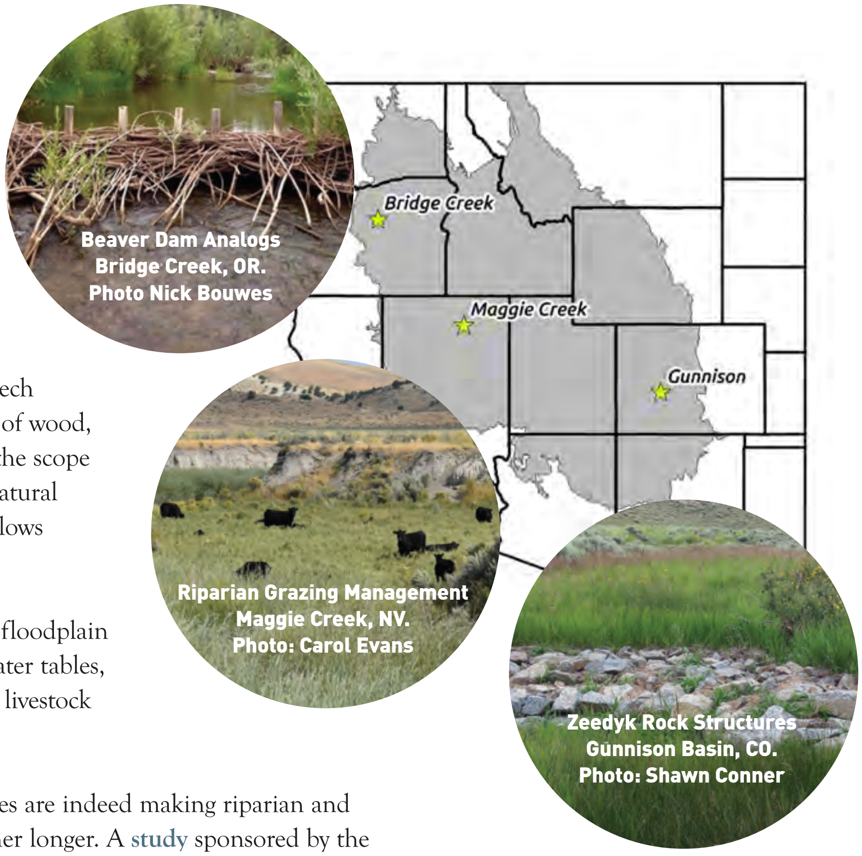
Science to Solutions

# Low-Tech Riparian and Meadow Restoration Keeps Rangelands Greener Longer

***In Brief:***

- Traditional approaches to riparian and wet meadow restoration are often intensive and expensive, limiting the extent to which they can be applied.
- Practitioners are increasingly turning to cost-effective, low-tech restoration options that restore soil moisture and improve vegetation, which can be more easily implemented at large scales.
- New research shows low-tech restoration methods effectively **increased vegetation productivity by 25%** and **kept plants greener longer** during the year.
- Restoration efforts also showed reduced sensitivity to precipitation over time, resulting in **greater resiliency** against the impacts of drought and climate variability.

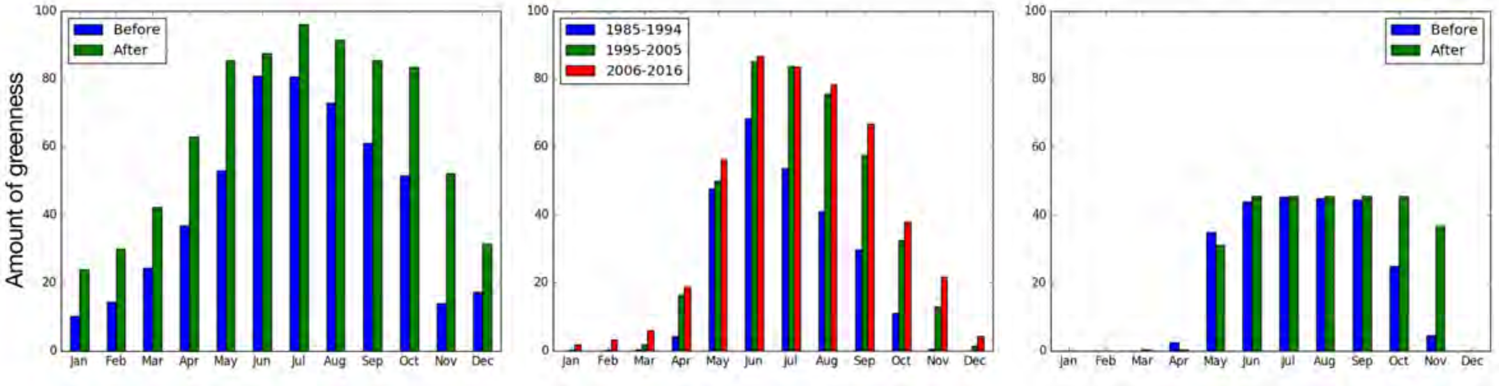
On semiarid rangelands in the western U.S., water is life. Wet habitats—like riparian areas, streams, and meadows—comprise less than 2% of the landscape but are vitally important for wildlife and livestock. Unfortunately, nearly half of these scarce resources are considered degraded. Traditional approaches to restoring riparian areas and wet meadows are often intensive and expensive, limiting the extent to which they can be applied.



Increasingly, practitioners are using more cost-effective, low-tech restoration methods—like simple hand-built structures made of wood, mud, and rocks—that can be more readily applied to match the scope of degradation. These techniques are designed to kickstart natural recovery processes with the least amount of money, which allows landowners and managers to treat areas on a larger scale.

Goals of low-tech wet habitat restoration include enhancing floodplain connectivity, boosting soil moisture retention, and raising water tables, which produces more 'green groceries' that feed wildlife and livestock in the late summer and early fall.

New research shows that these low-tech restoration techniques are indeed making riparian and meadow areas more productive, and helping them stay greener longer. A study sponsored by the NRCS-led Sage Grouse Initiative and the Bureau of Land Management evaluates the outcomes of three different low-tech wet habitat restoration projects around the American West.



Low-tech restoration methods increased vegetation productivity by up to 25% and kept plants greener longer during the year. Plus, Maggie Creek revealed added benefits of restoration with time: plant productivity was less sensitive to precipitation as the restoration effort matured, generating greater resiliency against the impacts of drought and climate variability. This study shows how low-tech restoration techniques implemented at appropriate scales are generating outcomes that are measurable from space.

## Methodology

Using freely available satellite imagery, the study quantified productivity using the Normalized Difference Vegetation Index (NDVI) at sites where various low-tech restoration methods were applied:

**1. Beaver Dam Analogs (Bridge Creek, Oregon)** – Simple hand-crafted structures made of wood, mud, and cobble were built to mimic natural dams and encourage beaver recovery in a perennial stream (evaluated 10 years post-restoration). These dams slow streamflow and reconnect floodplains, creating more wet habitat and green vegetation.

**2. Time-Controlled Grazing Management (Maggie Creek, Nevada)** – Changes in the livestock grazing season of use and watering points were implemented to promote riparian vegetation recovery along a perennial stream (evaluated 25 years post-restoration). Adjusting grazing locations and the timing of grazing helps streamside vegetation recover.

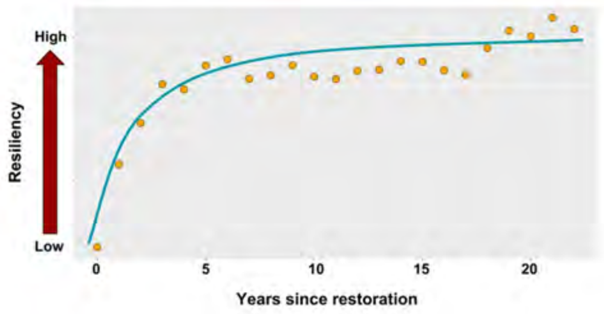
**3. Zeedyk Structures (Gunnison River Basin, Colorado)** Hand-built rock and wood structures were installed to improve hydrologic function of wet meadows and intermittent streams (evaluated 5 years post-restoration). These structures slow down flowing water to spread it across the landscape in order to reduce erosion and increase wetland vegetation.

## Source

Silverman, Nicholas L. et al. 2018. Low-tech riparian and wet meadow restoration increases vegetation productivity and resilience across semiarid rangelands. Restoration Ecology.

> *"Low-tech stream restoration helps put money in the piggy-bank when it's wet, so that wildlife, ranchers, and the ecosystem as a whole can draw upon the stored soil water during dry times."*
>
> ~Nick Silverman, study's lead researcher, University of Montana

Building Resiliency Over Time



## Science In Action

Through the Sage Grouse Initiative, the NRCS and partners provide technical and financial assistance for strategic practices that help landowners scale-up conservation of the West's precious water resources.

- Download resources from USDA-NRCS: Mesic Area Conservation For Sage Grouse.
- Use SGI Interactive Web App "Mesic Resources" mapping tool to help target wet habitat restoration and protection

The **Sage Grouse Initiative** is part of **Working Lands for Wildlife,** led by USDA's Natural Resources Conservation Service, which is a partnership-based, science-driven effort to proactively conserve America's working agricultural lands and wildlife.

SCIENTIFIC AMERICAN

CLIMATE

# Can Meadows Rescue the Planet from CO2?

## An unusual research project is determining whether restoring California's meadows can reduce atmospheric carbon dioxide

By Jane Braxton Little on May 11, 2017

The record piles of snow across California's Sierra Nevada are melting away, exposing once again its breathtaking alpine meadows. As temperatures warm the moist soil, the meadows quicken, cycling carbon from the ground into the atmosphere and back again in a pattern essential to the planet's health. Scientists and land managers are heading into the mountains to measure the greenhouse gas activity at 16 hand-picked meadows—some recently restored, others degraded from a century of grazing and logging.

The four-year study is part of California's pioneering effort to reduce carbon emissions. The project is designed to determine whether restored meadows hold more carbon than those that have been degraded. The outcome could prove pivotal for California and the planet. Worldwide, soils store three times more carbon than vegetation and the atmosphere combined. If the research shows restored meadows improve carbon storage, it could stimulate meadow restoration around the world.

The $4.8-million project has an unusual twist, too. It is funded by the California Air Resources Board, which wants to know if restored meadows can hold enough tonnage of carbon dioxide equivalents, per acre per year, to qualify as carbon credits in California's cap-and-trade market. "It's kind of geeky but we're poised to do something that's never been done with alpine meadows," says Mark Drew, Sierra Headwaters director at California Trout, who is coordinating the work.

Meadows are new to soil carbon research. Carbon enters the soil as plants use solar energy to draw carbon dioxide from the atmosphere and make their own food. More enters the ground when plants die and are decomposed by microbes. And yet living plant roots expel carbon dioxide, and so do microbes as they decompose the dead plant matter, creating a cycle of carbon uptake and emission by soil. It is common for agricultural land to lose a fair portion of its original carbon stock as it is relentlessly farmed—as much as 50 to 70 percent, according to several estimates. Scientists suspect meadows may lose carbon as well, especially when they are degraded by logging and grazing activities that compact soils, erode streams and deplete native plants and animals.

Sky Parlor Meadow in Tulare, California. *Credit: Miguel Vieira Flickr (CC BY 2.0)*

Some scientists also think global warming itself is changing soil carbon stocks. A December study published in Nature, led by Thomas Crowther at Netherlands Institute of Ecology, found rising temperatures are stimulating a net loss of soil carbon to the atmosphere. Warmer soils accelerate the flux, sending more carbon into the ground and more carbon dioxide back out into the atmosphere. As warmth increases microbial activity, decomposition and respiration outpace photosynthesis, particularly in the world's colder places. "That's when the losses start to happen," Crowther says. The changes could drive a carbon–climate feedback loop that could accelerate climate change.

Drew was already starting to collaborate with several meadow restoration groups in 2014, when the Air Resources Board announced funding to study carbon flux in Sierra meadows. Rather than compete for small pots of money, the various stakeholders decided to work together—PhD scientists side by side with ranchers and landowners. Together they could build a database far larger than any one project could, Drew says.

The group already knew meadow restoration—usually done with heavy equipment to fill braided channels and re-create functioning floodplains—has well-documented ecosystem benefits. Returning streams to their natural meanders and raising the water table rejuvenates habitat for golden trout, willow flycatchers and other endangered species. Restoring

Morning clouds over the Sierra Mountains in Bishop, California. *Credit: David H. Carriere Getty Images*

meadows also improves their capacity to store and release water, a boon to a state that depends on the Sierra region for more than 60 percent of its water supply. Spurred by Air Board funding, the meadow partners set out to see what restoration could do for carbon storage as well.

The research covers meadows from the base of Lassen Peak in the north to areas nearer to Los Angeles. The meadows range in elevation from 3,045 to nearly 8,700 feet; they include granitic, volcanic and metamorphic soils. A critical facet of the partnership is developing precise procedures for when and how to measure and analyze meadow greenhouse gases. Although scientists have established protocols for monitoring carbon flux in forests and wetlands, none exist for alpine meadows. “We’re the guinea pigs,” Drew says.

Work has just begun and will continue until winter closes access. The data collection begins with pushing an eight-inch segment of PVC pipe into the ground vertically to seal off a small segment of meadow, then capping the cylindrical chamber. A monitor pokes a syringe into a tiny hole in the cap, drawing a sample of whatever meadow gases are captured inside. By taking three samples 15 minutes apart repeatedly over several months scientists can compare the ambient air with gases coming directly out of the meadow. The rate of change in the concentration of gases determines the soil’s CO2 emission rate. The researchers are also monitoring soil carbon by extracting core samples. Comparing the data from restored meadows with geographically similar degraded sites will show the effects of restoration.

The researchers have a hint of what they might find from a limited study conducted by the University of Nevada, Reno (U.N.R.). Scientists collected soil samples at seven meadows in the northern Sierra restored between 2001 and 2016, pairing restored sites with similar, adjacent unrestored sites. The preliminary results found an average of 20 percent more soil carbon in restored meadows, with one site recording an increase of over 80 percent. Meadows immediately begin storing carbon following restoration, with significant increases over 15 years, says Cody Reed, a research assistant working with Ben Sullivan, a U.N.R. soil scientist and assistant professor. The investigation seems to show restored meadows add soil carbon and also slow losses to the atmosphere.

Another limited study looked at the effects of water in meadow soils. Steve Hart, an ecology professor at University of California, Merced, and Joseph Blankinship, assistant professor of microbial biogeochemistry at the University of Arizona, researched a Sierra meadow to understand how water affects the fluxes of carbon dioxide, methane and nitrous oxide. What they found surprised them: Carbon dioxide emissions were unaffected by soil moisture content, and methane sequestration was prevalent, particularly on the dry side of wet meadow. The 2014 study also found plant species richness and soil carbon concentration appeared more important than soil moisture in explaining carbon fluxes.

It is too soon to know if these results will be replicated on the larger Sierra-wide scale. With a full year of research already logged, Drew and his partners are digging in to a new season of fieldwork. A finding of dramatically increased soil carbon in restored meadows would have a limited effect globally because such large forces are at work. But the gain could be an important, added payoff for restoring these landscapes. The Sierra Meadows Partnership could also serve as a model to others working in very different landscapes that hold the potential to have a much greater effect on the carbon equation, Hart says. And if restored meadows do indeed hold significantly more carbon, then they could play a role in California's carbon market. The Sierra partners have until 2019 to present their results. “We’re poised to do something really unique,” Drew says. “Let's see where it takes us.”

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**Earth Surface Processes and Landforms**
*Earth Surf. Process. Landforms* **32**, 1174–1185 (2007)
Published online 3 July 2007 in Wiley InterScience
(www.interscience.wiley.com) **DOI:** 10.1002/esp.1553

# Geomorphic changes upstream of beaver dams in Bridge Creek, an incised stream channel in the interior Columbia River basin, eastern Oregon

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Received 1 October 2006;
Revised 16 February 2007;
Accepted 17 February 2007

## Abstract

**Channel incision is a widespread phenomenon throughout the dry interior Columbia River basin and other semi-arid regions of the world, which degrades stream habitat by fundamentally altering natural ecological, geomorphological and hydrological processes. We examined the extent of localized aggradation behind beaver dams on an incised stream in the interior Columbia River basin to assess the potential for using beaver, *Castor canadensis*, dams to restore such channels, and the effect of the aggradation on riparian habitat. We estimated aggradation rates behind 13 beaver dams between 1 and 6 years old on Bridge Creek, a tributary to the John Day River in eastern Oregon. Vertical aggradation rates are initially rapid, as high as 0·47 m yr$^{-1}$, as the entrenched channel fills, then level off to 0·075 m yr$^{-1}$ by year six, as the sediment begins accumulating on adjacent terraces. We found that a 0·5 m elevation contour above the stream channel approximately coincided with the extent of new riparian vegetation establishment. Therefore, we compared the area surrounding reaches upstream of beaver dams that were within 0·5 m elevation of the stream channel with adjacent reaches where no dams existed. We found that there was five times more area within 0·5 m elevation of the channel upstream of beaver dams, presumably because sediment accumulation had aggraded the channel. Our results suggest that restoration strategies that encourage the recolonization of streams by beaver can rapidly expand riparian habitat along incised streams.**

**Keywords:** **incision; aggradation; *Castor canadensis*; riparian; Oregon**

## Introduction

Channel incision is a common occurrence in stream channels throughout the semi-arid regions of the interior Columbia River basin, where a fragile balance between climate, vegetation and geology makes the vertical stability of channels highly vulnerable to changes in hillslope erosion, stream discharge and loss of instream retention elements (Cooke and Reeves, 1976; Welcher, 1993; Peacock, 1994). We define incision as a rapid downcutting and lowering of the stream bed such that it reduces the frequency and duration of flooding onto the adjacent floodplain (*sensu* Leopold *et al.*, 1964). Incision is a common response of streams to land use changes throughout much of the semi-arid regions of the American West and in other regions of North America, Africa, Australia, Europe, Asia, the Middle East and South America (Cooke and Reeves, 1976; Schumm *et al.*, 1984; Nagle, 1993; Prosser *et al.*, 1994; Simon *et al.*, 1995; Vandekerckhove *et al.*, 2000).

Incision has degraded instream and riparian habitat throughout the Columbia River basin, suggesting that restoration of such streams would benefit numerous species. Of particular interest is improving habitat for salmonids, because many of the Columbia River stocks are listed under the United States Endangered Species Act. Many streams in the Columbia River basin that historically supported salmon no longer do so, and habitat conditions are severely degraded in these incised streams (Nehlsen *et al.*, 1991; Elmore *et al.*, 1994; Wissmar, 1994). Incision can dramatically affect stream habitat for salmon and other fishes by the lowering of stream-adjacent water tables and the subsequent loss of riparian vegetation. The loss of above-ground vegetation reduces shading and organic inputs to the stream (Brown and Krygiier, 1970; Kiffney *et al.*, 2000), while the loss of below-ground roots increases the erodibility of stream banks (Smith, 1976). The lowered water tables also directly impact the stream by reducing groundwater inputs to the stream. This is a significant concern in semi-arid regions such as in our study area because many streams have incised to bedrock and therefore the water table is at or near the bedrock and there is little opportunity for water to be stored in the alluvium. As a result, many incised streams cease flowing or have substantially reduced flows in the summer because there is no baseflow provided by the alluvial aquifer (Elmore and Beschta, 1987). The loss of cool groundwater inputs also leads to increased summer stream temperatures (Poole and Berman, 2001). Further, incised streams rarely access their floodplains, high flows are concentrated within the incised channel, and fish have no access to slow-water refugia during floods (Harvey and Watson, 1986; Elmore and Beschta, 1987; Shields *et al.*, 1995). In contrast, numerous studies suggest that when local water tables of incised streams are raised, usually through the construction of beaver dams or small human-made dams, flows increase and intermittent streams become perennial (reviewed by Ponce and Lindquist, 1990; Pollock *et al.*, 2003).

The historical record suggests that numerous streams in the semi-arid region of the interior Columbia River basin once contained narrow, deep and gently meandering channels lined with dense riparian forests of cottonwoods, *Populus*, willows, *Salix*, and/or sedges, *Carex*, numerous beaver, *Castor Canadensis*, dams (which are generally constructed out of numerous pieces of small diameter (1–4 cm) wood and mud), abundant and easily accessible off-channel habitat on the floodplain and good flow and cool temperatures throughout most of the year (Buckley, 1992; Wissmar *et al.*, 1994). Today many of these same streams are incised and contain little or no riparian vegetation or beaver dams. Stream temperatures are high and flow is ephemeral (Elmore and Beschta, 1987; Buckley, 1992; Peacock, 1994; CBMRC, 2005).

Land use change, climate change or localized high intensity rainfall can cause channel incision, either by increasing the tractive force of water or by decreasing the resistance of the stream bed (Cooke and Reeves, 1976). Within the Columbia River basin, the exact mechanism that caused widespread channel incision remains uncertain, although its timing almost invariably followed the widespread trapping of beaver and the onset of intensive sheep and cattle grazing in the mid 19th and early 20th centuries (Russell, 1905; Buckley, 1992; Peacock, 1994). In other semi-arid regions, aggradation (recovery from incision) has been observed when grazing practices and riparian land uses are altered to allow the re-establishment of riparian vegetation (Zierholz *et al.*, 2001). Aggradation has also been observed to occur where beavers are able to build dams on streams (Scheffer, 1938; Butler and Malanson, 1995; McCullough *et al.*, 2005). This suggests that recovery will occur when natural processes are allowed to operate. However, the time frames for recovery may range from decades to centuries. Recovery rates are related to both the quantity of sediment entering a channel and the ability of the channel to retain this sediment.

Recovery of incised streams has both a physical and a biological component, though the two are interdependent. Physical recovery includes both the geomorphic and hydrologic changes that occur as a channel aggrades, while biological recovery includes the changes in riparian vegetation and instream biota that can either initiate or result from physical recovery. Much of the literature examining incised streams has focused on the changing geomorphic characteristics of such streams as they cycle through stable, incising and aggrading states (Leopold *et al.*, 1964; Schumm *et al.*, 1984; Darby and Simon, 1999). A general conceptual model has emerged regarding the channel evolution of incising streams (Figure 1). The model has numerous variants, but most include (a) a sequence of relative stability followed by (b) rapid downcutting such that the stream is isolated from its floodplain, (c) an increased stream width-to-depth ratio, a decrease in stream sinuosity and extensive widening of the incised trench, which eventually leads to (d) a stream at a lower base level and a lower longitudinal slope, with a new inset floodplain that develops a more sinuous planform and lower width-to-depth ratio, then (e) slow, long-term aggradation of the streambed and inset floodplain that (f) may or may not reach the level and the longitudinal gradient of the former floodplain before a new cycle of incision begins. Because the incision phase is rapid and causes dramatic physical and ecological changes, research efforts have focused on understanding causes of incision, to what extent they are the result of land use practices versus a natural phenomenon and how future incision can be prevented (Schumm *et al.*, 1984; Darby and Simon, 1999). Less attention has been focused on factors influencing the post-incision phases and in particular the factors that might influence aggradation rates (but see Shields *et al.*, 1999). Generally, it has been assumed that aggradation of incised streams is a slow process that operates on a multi-century timeframe, and that extensive widening of the incision trench must occur prior to aggradation (Leopold *et al.*, 1964; Schumm *et al.*, 1984; Rosgen, 1996). However, such assumptions are based almost entirely on the physical principles of sediment transport in fluvial systems, and do not include the effects of large wood, beaver dams (i.e. small wood) or riparian vegetation on sediment transport and deposition and the modification of fluvial landforms. Nonetheless, the channel evolution model illustrated in Figure 1 provides a framework for understanding the sequence of geomorphic changes that might be expected to occur following incision and how aggradation rates might be altered by large wood, live vegetation or beaver dams.

Live vegetation, particularly dense, emergent graminoids such as sedges, has been shown to effectively remove suspended sediment from water columns, primarily by creating a low velocity zone near the stream bed, which allows

DOI: 10.1002/esp

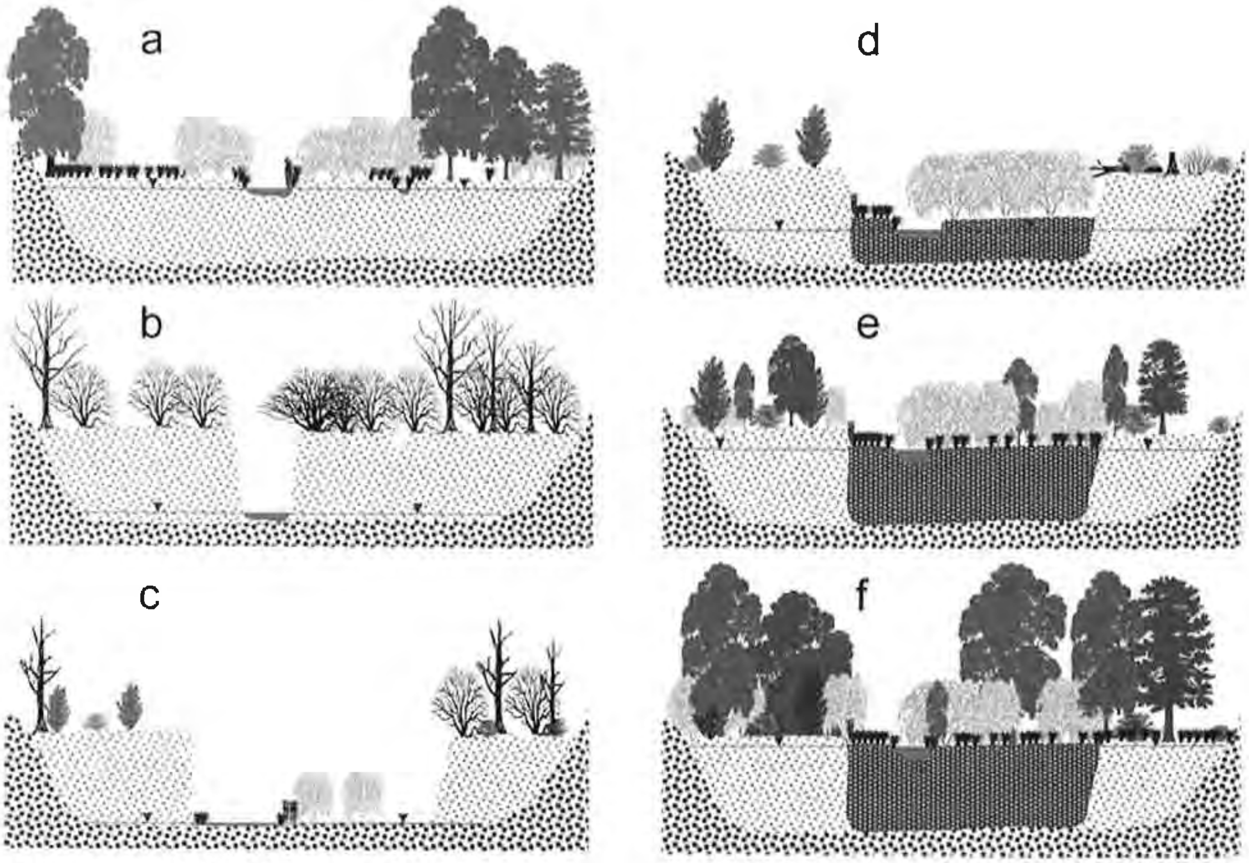

**Figure 1.** Conceptual diagram of incision and filling cycle in a semi-arid environment such as the interior Columbia River basin. (a) A fully aggraded stream connected to its floodplain and a water table near the floodplain surface. (b) Incision is triggered, usually by a change in land use practices that result in increased stream power. The water table lowers, resulting in the death of riparian vegetation. The channel is confined to a narrow trench. (c) Eventually, the incision trench widens as the channel develops meanders, and a narrow floodplain establishes with a greatly diminished riparian area. Xeric plant communities dominated by juniper and sagebrush develop on the former floodplain. (d) Floodplain vegetation such as sedges and willows trap sediment during high flows, and the developing meandering pattern of the stream lowers the stream gradient. Within the incised trench, aggradation begins to occur and the water table rises. (e) Over time, continued aggradation begins to reconnect the stream to its former floodplain, and the water tables continue to rise. During this period, plant diversity is high because both xeric and riparian species are present. (f) As conditions become more favorable to riparian species, the xeric species die out and riparian plant biomass continues to increase. The stream and riparian forest return to the pre-incision state.

fine-grained material to settle out of suspension (Elliot, 2000; Braskerud, 2001; Carollo *et al.*, 2002). Establishment of emergent vegetation following the cessation of cattle grazing has been implicated as an important prerequisite for aggradation of incised streams in the semi-arid regions of Australia (Zierholz *et al.*, 2001). Similarly, beavers affect sediment transport when they dam small streams by weaving together numerous small pieces of wood and packing the interstices with mud (Morgan, 1986). The dams create low velocity stream reaches where sediment can drop from suspension. Additionally, they often raise the water level such that it permanently floods the adjacent floodplain or low terrace, thus creating a large shallow littoral zone suitable for the establishment of emergent and other riparian vegetation (Pastor *et al.*, 1993). Thus beaver dams should affect sediment transport by directly influencing stream velocities, and indirectly by creating an environment conducive to the establishment of emergent vegetation that traps sediment. The geomorphic effects of beaver dams has been documented (reviewed by Gurnell, 1998; Pollock *et al.*, 2003), though few studies have examined aggradation rates and only one has done so in an incised stream (McCullough *et al.*, 2005). Butler and Malanson (1995) estimated sedimentation rates of 0·02–0·28 m yr$^{-1}$ above four beaver dams in Glacier National Park, MT, while Meentemeyer and Butler (1999) observed average sediment depth of 0·28 m in five ponds 5 yrs old or less (i.e. a minimum aggradation rate of 0·06 m yr$^{-1}$), in Glacier National Park, MT, while Scheffer (1938) observed aggradation of 0·55 m over a two year period on a small tributary to the Columbia River in eastern Washington. Naiman *et al.*

(1986) estimated that $3.2 \times 10^6$ $m^3$ of sediment were stored behind all the beaver dams in second-fourth order streams in their study area in Quebec. They calculated that if this sediment were distributed evenly across all the streambeds, it would raise them by 42 cm. McCullough *et al.* (2005) studied beaver colonization of an incised stream in Nebraska and found that in a reach where beaver had been established for 12 years stream bed aggradation averaged 0·65 m.

Field observations of small incised streams within the Columbia River basin suggest that incision depths typically range from 1 to 2 m, less frequently up to 5 m and in some extreme cases may incise as much as 20 m (see, e.g., Peacock, 1994). The aggradation rates behind beaver dams reported in the literature suggest that where beaver dams are present in incised streams aggradation may occur at a rate sufficient to reconnect a stream to its former floodplain on decadal timescales, thus increasing projected rates of recovery by an order of magnitude or greater over recovery estimates when it is assumed no beaver dams are present (see, e.g., Rosgen, 1994).

Because we know that historically beaver were abundant throughout the semi-arid regions of the Columbia River basin (Johnson and Chance, 1974; Buckley, 1992), we hypothesized that their reestablishment in incised streams could greatly increase aggradation rates and accelerate the recovery of stream and riparian habitat. The purpose of this study was to assess volumetric and vertical aggradation rates of beaver ponds in an incised stream and to estimate the projected time to accumulate the sediment necessary to reconnect the stream to abandoned floodplain terraces.

## Site Description

The Bridge Creek watershed is a 710 $km^2$ watershed draining directly into the lower John Day River in eastern Oregon (Figure 2). Elevation ranges from 499 m at the mouth to 2078 m at the summit of Mt. Pisgah. The basin is dominated by sagebrush-steppe, *Artemisia*, and juniper-steppe, *Juniperous occidentalis*, in the lower elevations, with the vegetation changing progressively to forests dominated by Ponderosa pine, *Pinus ponderosa*, Douglas-fir, *Pseudotsuga menziesii*, and then spruce, *Picea englemannii*, with increasing elevation. Most of the mainstem and lower tributary reaches of Bridge Creek are incised and thus the riparian vegetation is limited to a very narrow band along the stream. Riparian vegetation is dominated by willows, but cottonwood is present in some areas, as are a variety of shrubs. High flows in Bridge Creek occur during the spring, when runoff from the melting snowpack raises water levels to near bankfull height for weeks at a time. Peak flows also occur during this time, typically when localized storm cells provide high amounts of precipitation that add to the existing high water levels. Maximum

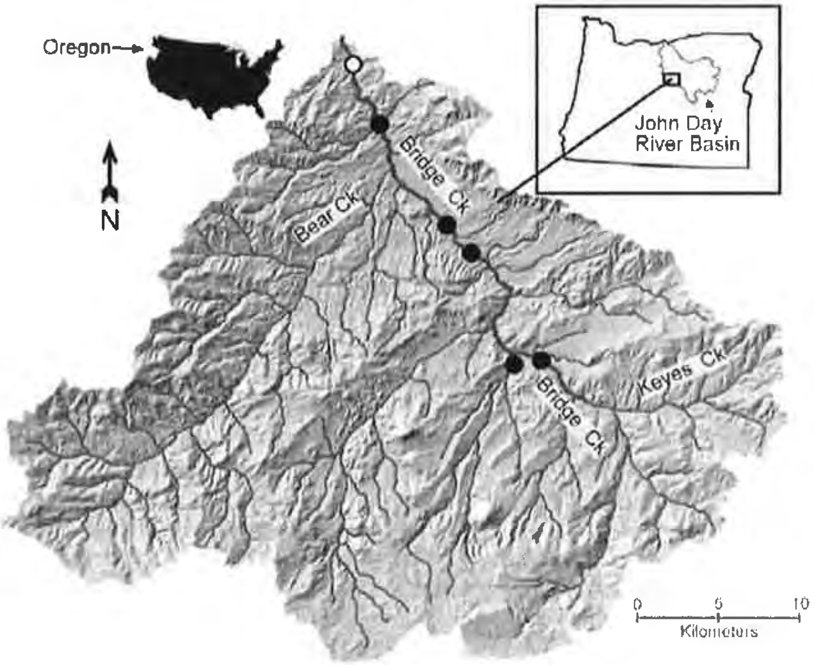

**Figure 2.** Bridge Creek drains a 710 $km^2$ basin into the lower John Day River in eastern Oregon. The John Day is a major tributary to the Columbia River. The black dots on the map of Bridge Creek are the general areas where beaver ponds are located. The white dot is the location of the gauging station.

DOI: 10.1002/esp

estimated peak flow in Bridge Creek near the mouth is 28 $m^3 s^{-1}$, while late-summer low flows have been measured as low as 0·15 $m^3 s^{-1}$ (Anna Smith, BLM, Prineville, OR, personal communication).

The surficial geology of Bridge Creek is dominated by thick layers of basalt and andesite that originated from numerous lava flows of the Eocene and Oligocene period. There are also substantial areas of highly erosive volcanic ash known as the John Day Formation that also originated from a series of volcanic eruptions in the Oligocene and Miocene. The lower main valley of Bridge Creek is surrounded by cohesive, fine-grained quaternary alluvium, much of which is derived from the ashes of the John Day formation.

Bridge Creek and its tributaries are utilized by an anadromous run of Middle Columbia steelhead, *Oncorhynchus mykiss*, that are part of the ecologically distinct Lower John Day population, which occupies the lower, drier Columbia Plateau ecoregion within the John Day Subbasin, and are listed under the Endangered Species Act (CBMRC, 2005). Bridge Creek is a priority watershed for restoration because its salmonid production and abundance potential is high (CBMRC, 2005). Chinook salmon have also been recently documented in Bridge Creek (M. Pollock, personal observation, June 2007). Habitat quantity, temperature, sediment load, habitat diversity and flow have been identified as limiting factors in Bridge Creek. Summer stream temperatures in Bridge Creek frequently exceed 27 °C when stream flows are at a minimum. Not surprisingly, Bridge Creek is on the 303(d) list of temperature impaired streams (CBMRC, 2005). Due to the erosive nature of some of the geologies, and in particular the large number of incised, failing stream banks, sediment loads are high in Bridge Creek, especially during peak flow events.

## Methods

Sediment accumulation behind 13 beaver dams was estimated by establishing a grid of points upstream of the dam. Transects were spaced every 10 m upstream and sediment depth measurements were made every 5 m along each transect. Sediment depth was estimated by pushing a sediment corer through the surface layer of fine-grained unconsolidated sediment until a more compact layer was reached, which often contained larger clasts such as gravels. A clear boundary between loose, fine-grained surface material underlain by more compact, coarser-grained material existed at almost every point. The aggradation of unconsolidated fine-grained material was assumed to be recently deposited and to result from the construction of the beaver dam downstream. This was a reasonable assumption because sites that had no beaver dam downstream had no layer of fine-grained unconsolidated sediment, while all sites we examined upstream of beaver dams contained such a layer.

The age of the 13 beaver dams was determined from a database provided by the Bureau of Land Management, Prineville office. The BLM has been surveying for beaver dams along the mainstem of Bridge Creek for over a decade and has a GIS layer identifying the location of each beaver dam and each year that it has been present.

Digital orthophotographs for the mainstem of Bridge Creek were obtained from a three-band color imagery and light detection and ranging (LIDAR) survey of Bridge Creek from the mouth to approximately 28 km upstream to the town of Mitchell that was flown in September 2005 by Watershed Sciences, Portland, OR. The area within 0·5 vertical elevation of the stream channel was estimated by using the LIDAR coverage to develop 0·5 m contour bands above the existing stream, which were then verified in the field. Field observations and analysis of the orthophotos indicated that most recently established riparian vegetation was found within 0·5 m of the current stream bed. Thus the 0·5 m elevation contour above the streambed is a reasonable approximation of where riparian vegetation is at present or might be expected to establish in the near future.

The bed slope above 18 beaver dams (another 5 in addition to the 13 where sediment accumulations were measured) and reaches above and below the area of aggradation above the dam were estimated using a DEM grid generated from the LIDAR coverage. The vertical accuracy of the LIDAR is 4–7 cm, and the DEM grid cells are 0·5 $m^2$. Slope measurements were also made in the field to verify the accuracy of the remote sensing measurements.

## Results

The aggradation rate decreased with age and was described by the power equation

$$AR = 0{\cdot}3835\ \mathrm{Age}^{-0{\cdot}9093} \qquad (1)$$

where AR is the aggradation rate, measured in m $yr^{-1}$, and Age is the dam age, measured in years ($r^2 = 0{\cdot}72$, $n = 13$; Figure 3). The data indicate initially high rates of aggradation, as much as 0·45 m in the first year, followed by a rapid decline and leveling off towards 0·075 m $yr^{-1}$ by year six (Figure 3). Volumetric sediment accumulation rates among the 13 sites were variable, averaging 171 $m^3 yr^{-1}$, with a minimum of 17 $m^3 yr^{-1}$ and a maximum of 522 $m^3 yr^{-1}$. A

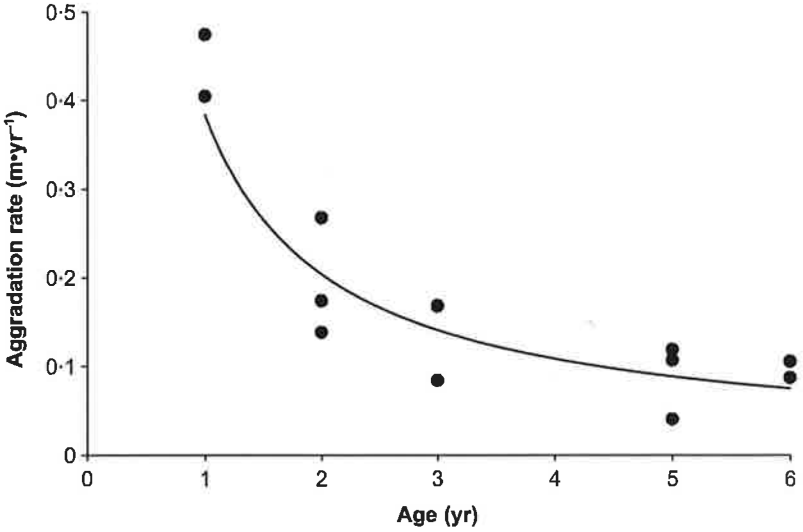

**Figure 3.** The relationship between beaver dam age and the aggradation rate (AR) upstream of the dam is described by the power equation $\text{Age} = 0{\cdot}3835\ \text{AR}^{-0{\cdot}9093}$ ($r^2 = 0{\cdot}72$, $n = 13$, $p < 0{\cdot}001$).

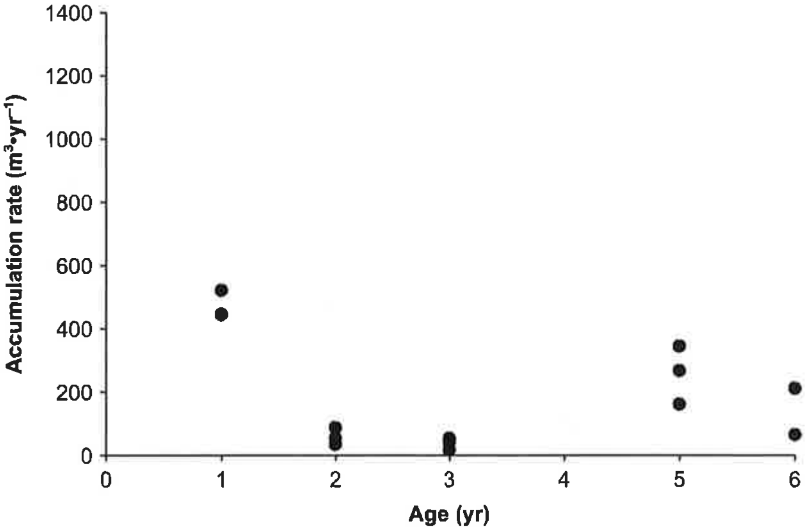

**Figure 4.** There was no significant overall trend between annual volumetric sediment accumulation rates and beaver dam age (linear regression: $p = 0{\cdot}6$, $r^2 = 0{\cdot}02$, $n = 13$), though both one-year-old dams did have the highest annual rate of volumetric sediment accumulation.

linear regression indicated no significant trend in the volumetric accumulation rate with age ($p = 0{\cdot}6$, $r^2 = 0{\cdot}02$, $n = 13$, Figure 4).

Sediment accumulations behind the beaver dams changed the bed slope. Upstream of beaver dams, bed slopes ranged between 0·001 and 0·014, averaging 0·004 (Figure 5). The underlying bed slopes ranged between 0·008 and 0·028, averaging 0·018. On average, the sediment accumulations reduced slopes by a factor of 4.5 or an average reduction in slope of 1.3%. In no instances did sediment accumulation behind beaver dams increase the slope of the stream.

Immediately upstream and downstream of the channel reaches where sediment accumulation occurred, the width of the area within 0·5 m elevation of the stream channel was remarkably consistent, averaging 8.6 m, with a range of 7.5–12.0 m. In contrast, where aggradation had occurred, the width of area within 0·5 m elevation increased and also became more variable, ranging from 16 m to 105 m, and averaging 44 m. The difference in widths between where aggradation had occurred and the average of the adjacent upstream and downstream reaches where aggradation had not occurred was significant (paired *t*-test, $p < 0{\cdot}001$, $n = 18$).

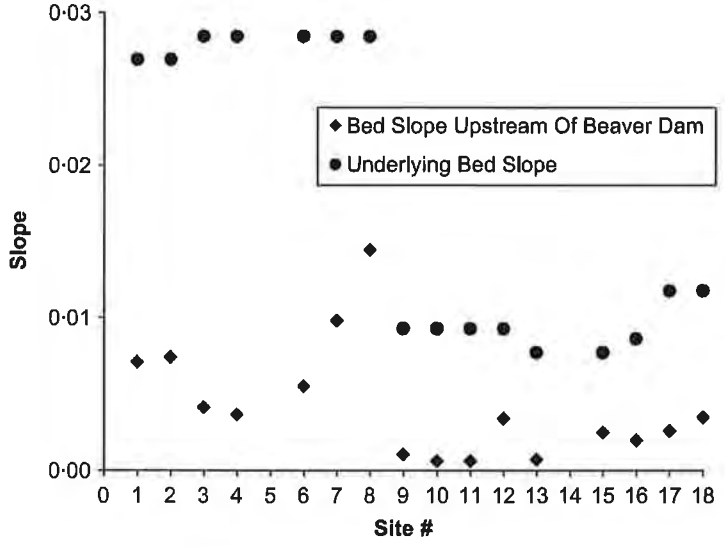

**Figure 5.** The accumulation of sediment behind beaver dams consistently lowered the slope of the stream bed. Upstream of beaver dams, bed slopes averaged 0·004, while the underlying bed slopes averaged 0·018. Circles mark the underlying bed slope; diamonds mark the bed slope immediately upstream of the beaver dam.

Based on the observed relationship between aggradation rates and dam age (Equation (1)) as well as other published literature on sediment accumulation rates (Scheffer, 1938; Butler and Malanson, 1995; McCullough *et al.*, 2005), we conservatively assumed a long-term (decadal) aggradation rate of 0·05 m $yr^{-1}$ above intact beaver dams. We used this rate to estimate the increase in the area within 0·5 m vertical elevation of the channel that will occur over the next 90 years for which there are active beaver dams in a reach. We made this estimate for five aggrading reaches where beaver dams currently exist to illustrate how different geomorphic conditions will affect recovery rates (Figure 6). Because beavers do not continuously occupy a site, the actual time it will actually take for this aggradation to occur

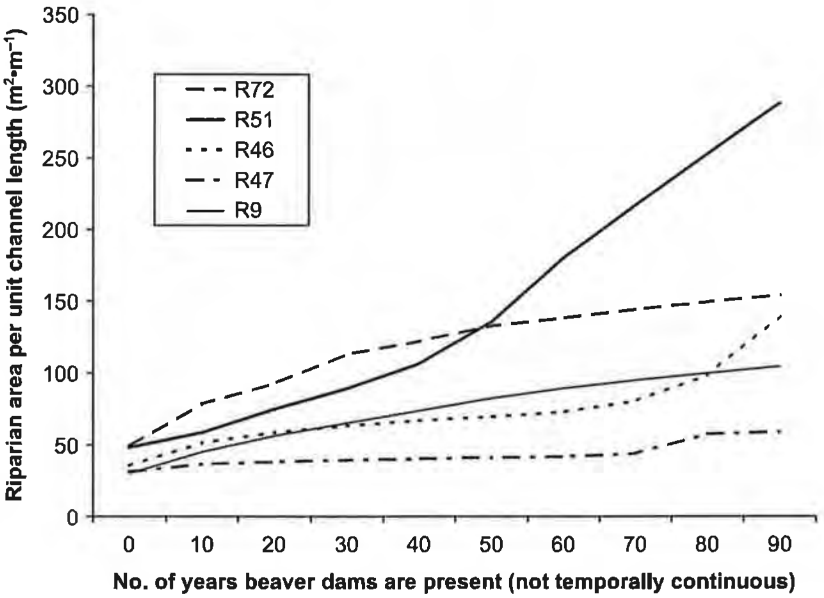

**Figure 6.** Estimated increase in stream-adjacent area within 0·5 m of the channel bed (i.e. the riparian area) as a function of the number of years for which the reach has active beaver dams, for five reaches on Bridge Creek that currently contain beaver dams. An aggradation rate of 0·05 m for each year for which beaver dams are present is assumed. The rate of increase of riparian area varies as a result of different degrees of incision and post-incision channel widening.

will be dependent on the relative amount of time for which beavers are maintaining active dams in the reach. Thus the temporal scale on the *x*-axis is 'number of years with beaver dams' rather than 'years'.

For these five reaches, the average amount of riparian area per unit of channel length initially was between 25 and 50 $m^2 m^{-1}$. After a cumulative 90 years of beaver dams at each of the sites, the projected amount of riparian area increase ranged from a less than twofold to a more than sixfold increase (Figure 6). This variation was a function of the depth of incision, the location of abandoned terraces and the width of the valley floor.

## Discussion

Our results demonstrate that within incised stream trenches beaver dams create an environment favorable for the deposition of suspended sediment. The beaver dams in our study area have already trapped enough sediment to raise the stream bed and reconnect the stream to low-lying terraces such that there was a fivefold increase in stream-adjacent area within 0·5 m elevation of the streambed. We observed that most areas within 0·5 m elevation of the streambed were being rapidly recolonized by emergent and woody riparian vegetation, particularly at the older sites. In some instances, sedimentation behind existing beaver dams has aggraded streams sufficiently to reconnect them to abandoned terraces, thus greatly expanding the areal extent of riparian vegetation (see, e.g., Figure 7).

Most models of the channel evolution of incised or inciseable streams concur that after a period of rapid incision the incision trench widens and a new inset floodplain is formed. Then the long process of aggradation begins as sediment accumulates on the inset floodplain during floods (see Figure 1). Our results suggest that the presence of beaver dams substantially alters this basic model. Beavers used small-diameter wood and mud to build small (generally <1·5 m high) dams on incised streams that had not yet widened. The dams created a slow-water environment that allowed sediment to drop out of suspension. At some (but not all) of our study sites, the incised streams had not yet gone through the widening phase, and the incision trench was able to rapidly fill with sediment, so the stream bed quickly aggraded. In several instances, the aggradation had already raised the stream bed sufficiently to connect the stream to formerly abandoned terraces (see, e.g., Figure 7), demonstrating that under proper conditions recovery of incised streams can occur over very short time frames. This is a significant finding, because a current scientific paradigm in

**Figure 7.** An aerial orthophotograph of beaver dams (green lines) and riparian vegetation adjacent to Painted Hills National Monument. The red line outlines the stream-adjacent area within 0·5 m elevation of the existing stream channel. The large, downstream beaver dam has aggraded the stream bed over 1 m in the past 6 years, raising the water table and allowing riparian vegetation to rapidly expand onto a formerly abandoned terrace such as the one immediately upstream.

DOI: 10.1002/esp

regard to the restoration of incised streams in the western United States assumes that the most practical way to accelerate the restoration of incised streams is to assist in the creation of a new inset floodplain and to create a new sinuous channel within the new floodplain (Rosgen, 1996). Needless to say, this approach requires the extensive use of heavy machinery and involves a tremendous amount of work and expense. As Figure 1 suggests, it also delays the full recovery of some of the hydrologic functions of the stream by delaying the rise of the water table within the stream-adjacent alluvium. In contrast, a number of examples exist where the construction of beaver dams or small check dams allowed streams to aggrade and water tables to rise, and formerly seasonal streams developed perennial flow (Stabler, 1985; DeBano and Heede, 1987; Ponce and Lindquist, 1990; Pollock *et al.*, 2003). Thus restoration strategies that widen the incision trench to construct an inset floodplain can actually delay recovery of an important hydrologic function and cause long-term damage to the system as a whole.

We did not observe any degradation of ecosystem function caused by the presence of beaver dams within incised streams. Rather than creating an inset floodplain, the dams often simply created conditions such that the stream could rapidly aggrade to the level of the former floodplain. In addition to the expansion of riparian vegetation observed at some of our sites, we also noted in late summer that below the dams were pockets of cool water that averaged 4·1 °C lower than the ambient stream temperature (Figure 8), presumably a result of upwelling from beneath the dam (see, e.g., White, 1990). Additionally, we also observed considerably higher abundances of juvenile steelhead in the aggrading reaches (Pollock *et al.*, in review). Collectively, these observations suggest that a number of stream ecosystem attributes are responding favorably to aggrading reaches and the corresponding rise in alluvial water tables, though cause and effect relations have not been determined.

Not all reaches dammed by beavers have created large areas suitable for colonization by riparian vegetation. Some dams have been constructed in narrow, deeply incised reaches that will require several meters of aggradation before they will be reconnected to any abandoned terraces. Figure 6 illustrates the differences in projected future riparian areas as aggradation occurs behind beaver dams for five different reaches where beaver dams currently exist. Reach 51 has aggraded substantially and has already reconnected to several abandoned terraces. When beavers have maintained dams there for a total of 50 years, it will reconnect to several other low terraces, widening the riparian area to about 100 m, until it reaches the valley floor, whereupon there will be rapid expansion of the width of the riparian area across the valley floor to a width of 300 m or more. In contrast, Reach 9 is in a fairly confined valley that has gently sloping colluvial fans on either side. Even with extensive aggradation, the area within 0·5 m vertical elevation of the stream bed remains limited, and the riparian width is unlikely to ever be much greater than 100 m. Reach 72 is similar to Reach 9 in that it has alluvial fan on one side, so there is a limited area of valley floor for the channel to climb up onto, but there are several large, low-lying abandoned terraces that it can access as it aggrades. Ultimately, however, rapid riparian expansion is limited to about 150 m by the colluvial fan. Reach 46 is deeply incised and has a small

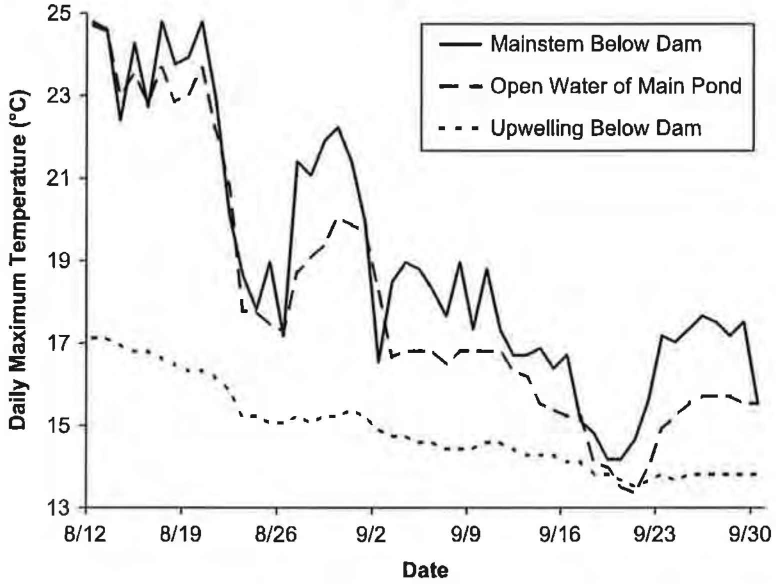

**Figure 8.** Temperature profiles of lower Bridge Creek in late summer 2005, showing that relatively cool pockets of water with mild temperature fluctuations exist below beaver dams, presumably the result of accumulated pond water above the dams downwelling through the alluvium and then upwelling below the dam (see White, 1990).

inset terrace that has been abandoned as more incision occurred, but is close to being reconnected to the channel as aggradation behind beaver dams continues. However, once this occurs, there will be little riparian area expansion until beaver dams have been in the reach for about 7 decades, when enough aggradation will have occurred to reconnect the stream to the abandoned terrace approximately 3·5 m above the current stream channel.

Because it is unlikely that beaver will occupy any site continuously for a duration long enough to reconnect the stream to an abandoned terrace, the axis of Figure 6 refers to the number of years for which beaver dams are present, rather than years. We use this metric because beavers do not continually occupy a site. However, several studies of beaver pond occupation and abandonment under natural conditions suggest relatively high occupancy rates once a site is colonized. Data from Johnston and Naiman (1990a, 1990b), who studied the patch dynamics of beaver pond creation and abandonment over a 46 year period across the 294 km$^2$ Kabetogama Peninsula in Voyageurs National Park, MN, suggests a pond turnover rate of less than 20% per decade, and a slow but ongoing increase in the total area occupied by beavers at the end of the study period. The total area affected by the beaver dams was about 13% of the total Peninsula area, and many streams were impounded to such an extent that they formed a continuous series of ponds and had occupied almost all of the reaches that could be dammed. A 20% turnover rate suggests that 80% of the dammable reaches are dammed at any particular time, and that on average any given site has a dam on it for 80% of the time (see also Naiman *et al.*, 1988).

Data from Snodgrass (Snodgrass, 1997 – Figure 4) suggests that 40 years after reintroduction of beavers to a 77 000 ha protected area near the Savannah River in South Carolina less than 15% of the sites colonized had been abandoned. This indicates an 85% occupancy rate. Remillard *et al.* (1987) studied patch dynamics of beaver ponds in Adirondacks State Park in New York over a 42 year period and found that the beaver had colonized most of the suitable habitat, and that the cycle of beaver pond colonization, abandonment and recolonization ranged between 10 and 30 years, but did not specify the average duration for which the ponds were occupied. This is consistent with the work of Neff (1959), who summarized 70 years of observations of a beaver pond in the Rocky Mountains of Colorado and found that it had been abandoned twice over that time (for 16 and 8 years) but had been continuously occupied for the previous 30 years (occupied 66% of the time). The 16 year abandonment is a little anomalous in that it was the result of a forest fire that destroyed the beaver colony. In general, site abandonment by beavers is often attributed to a depletion of the food supply and reoccupation of abandoned sites attributed to regeneration of food supplies (Hall, 1971; Hodgdon, 1978).

Bridge Creek is a sediment-rich stream in a semi-arid environment, so the cited occupancy rates are not directly applicable, but they do suggest that under a variety of natural conditions, with trapping pressures removed, beaver populations will expand to colonize most of the suitable habitat and then maintain a relatively high occupancy rate of that habitat. Our own observations of Bridge Creek suggest that many dams are abandoned because they rapidly backfill with sediment during one or two storm events, and the system of canals and pools that beavers need to provide protection while accessing their foraging areas, lodges and dams cannot be maintained.

Not all incised reaches contain beaver dams, even though the BLM database indicates that they have been there for brief periods (mostly ≤2 yrs) in the past. Observations along these reaches suggest that they are geomorphologically similar in terms of stream gradient and the width of the incision trench. However, most sites without beaver dams also have limited amounts of riparian vegetation, usually just a narrow corridor of small-diameter (<1 cm) willows alongside the stream. In contrast, sites with beaver dams have much more abundant riparian vegetation (see, e.g., Figure 7). We speculate that beaver have not dammed additional reaches because of a lack of vegetation needed both for food and for the construction of dams and lodges. This is a reasonable hypothesis because the hydrologic and geomorphic conditions are clearly suitable, as evidenced by the existing colonies along Bridge Creek. Predation (and trapping) is another potential factor limiting the establishment of beaver colonies along Bridge Creek, and may be the ultimate fate of the young beavers that disperse each year from the colonies. However, vulnerability to natural predation is a function of the extent to which beavers can build dams to create ponds and lodges where they are safe.

Thus it is possible that for an incised stream to recover it needs riparian vegetation in order for beaver dams to be built, but for riparian vegetation to widely establish, beaver dams need to be constructed. This would explain why an incised stream such as the mainstem of Bridge Creek, most of which is has recently been put in the public domain and is not subject to much grazing or agricultural pressures within the riparian corridor, does not contain more riparian vegetation and has only a few reaches that are actively aggrading. In this system, it appears that aggradation is dependent on the presence of both riparian vegetation and beavers, suggesting that aggradation rates have biological controls as well as physical controls. From a restoration perspective then it does make sense, at least initially, to create inset floodplains in some reaches so that enough riparian vegetation can become established to support beaver colonies. A less expensive restoration approach would be to provide beaver with the woody material needed for food and dam construction. This approach has been tried elsewhere briefly to restore incised streams, with positive results (Apple *et al.*, 1983; Apple, 1985). Dams were constructed and they quickly backfilled with sediment. However, the long-term fate of the beavers and the dams were not documented and it did not appear that the experiment was carried out for long enough for a colony to become permanently established.

If the number of beaver dams were increased throughout Bridge Creek, through either natural or artificial means, it is reasonable to ask whether at some point the system would become sediment supply limited, such that aggradation rates in dammed reaches would decrease. To answer this question, we estimated the existing annual sediment yield in Bridge Creek and compared it with the sediment retained by the beaver dams we examined in this study. We estimated sediment yield by two methods: (1) by using the Revised Universal Soil Loss Equation (Renard *et al.*, 1997) and (2) by using instream sediment loads measured over a three year period at a United States Geological Survey gauging station at Bear Creek, a nearby incised stream with a similar geology and a slightly smaller watershed size. The RUSLE approach estimated a soil loss of 0·05 mm $yr^{-1}$ or a total annual sediment volume of 34 850 $m^3$. The USGS data, after adjusting for the differences in drainage basin size, yielded an estimated annual sediment volume of 52 900 $m^3$, which is equivalent to a soil loss rate of 0·08 mm $yr^{-1}$. The total sediment retained by all of the beaver dams in our study was 7200 $m^3$ and the mean dam age was 3 years. This suggests that, adjusted to an annual basis, the 13 beaver dams removed between 5 and 7% of the total sediment load. Thus we conclude that the number of beaver dams in Bridge Creek could increase substantially, by at least an order of magnitude, before there was any measurable change in average aggradation rates upstream of the dams.

## Acknowledgements

We would like to thank Jason Hall and Sarah Baker for helping to collect the field data. Special thanks to Adam Mouton of the NWFSC GIS laboratory for his assistance with the LIDAR analysis, to Rick Demmer of the Bureau of Land Management, Prineville, OR, for providing us with the database of beaver dam locations and ages for Bridge Creek and to John Faustini of Oregon State University for providing the RUSLE soil loss estimates. We would also like to thank two anonymous reviewers, whose comments on this manuscript helped to improve its quality. This research was funded by the Northwest Fisheries Science Center 2005 Internal Grants Program.

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# THE POND-AND-PLUG TREATMENT FOR STREAM AND MEADOW RESTORATION: RESOURCE EFFECTS AND DESIGN CONSIDERATIONS

## A Briefing Paper for Plumas National Forest Resource Specialists and Managers

**The Red Clover – McReynolds Project, the first spring after construction (2008) (Photo: Jim Wilcox)**

**Version 1.0**
**May 2010**

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## Executive Summary

This paper is intended to provide a description of the pond-and-plug treatment, briefly present general treatment effects, and discuss basic design considerations relative to potential risks of the treatment. This paper's audience is intended to be Plumas National Forest (PNF) resource specialists and managers who may or may not be familiar with the technique. A primary goal of this paper is to document the Forest's current understanding, across several resource areas, of effects associated with the treatment as well as to point out gaps in our understanding that should be addressed by future monitoring or research.

Nowhere has this technique been employed to a greater extent than in the meadows of the Upper Feather River watershed. Implementation of pond-and-plug projects has intensified in recent years, with more than twice as many projects constructed since 2002 than were constructed in the 7 years prior.

Several factors have contributed substantially to these phenomena. The pond-and-plug technique results in both reconnection of a stream channel with a functioning floodplain and restoration of a degraded meadow's water table up to its historic level. The restored floodplain facilitates much less flood-flow stress along the restored channel so that stream banks are stabilized with less risk of future maintenance or reconstruction. Restoration of the meadow water table results in re-watering of meadow soils and vegetation, with significant effects throughout the restored floodplain for meadow hydrology, wildlife, and forage. Restored floodplain connectivity spreads flood flows so that a meadow's natural ability to settle the coarse or fine sediment delivered from steeper stream reaches is restored, a function that is especially critical where anthropogenic changes to the upper watershed have altered hydrology and increased sediment loads.

These effects are substantially realized within the first year after construction. Upper Feather River meadows have suffered severe degradation due to human-caused activities over the past 150 years, converting the meadows to dry lands with channel banks in a highly erodible state and local vegetation and wildlife communities that are far removed from historic condition. Due to efficiencies associated with construction, the technique allows restoration practitioners to economically treat larger lengths of these degraded systems than had been possible with past restoration techniques, with a wider array of potential benefits.

The technique is relatively new. Dramatic improvements have been observed at projects completed to date and reliable project design techniques have continually developed over the past 15 years. However, there is still much to be learned about several aspects of long-term ecological effects and project design elements will continue to evolve, particularly for steeper stream and meadow systems.

### Treatment Description

The stream and meadow restoration technique commonly known as "pond-and-plug" was first implemented on the PNF in 1995. The vast majority of pond-and-plug projects in the Upper Feather River watershed have been designed and implemented by the Feather River Coordinated Resource Management group (CRM).

Briefly described, this restoration technique obliterates an existing, incised ("gullied") stream channel, typically 3-10 feet deep, and redirects flow to a stable channel that is connected with a broad floodplain during annual peak flow events. The post-project channel is more stable because, when subjected to floods, flow accesses the channel's floodplain and spreads out over a broad area. As a result, flood flows are much shallower and less erosive and conditions for streamside vegetation establishment and maintenance are improved. The pre-project incised channel is obliterated by constructing a series of earth plugs. Import of enough material to completely fill in the gully is extremely costly. Instead, the gully is widened both upstream and downstream of each plug to provide the borrow material. When the stream is re-located to the meadow surface, the water table rises and the widened gully areas fill with ground water, resulting in a series of ponds that are as deep as the original gully.

General "dos and don'ts" associated with stream restoration projects apply also to projects in which pond-and-plug is an alternative. For any stream restoration project, it is important to develop an understanding of the current condition and the factors, both natural and anthropogenic, that have shaped that condition. Prior to initiating a restoration project, it should be clear why the project meadow has degraded more quickly than what would occur naturally. Also, it is imperative that the specific project objectives be clearly communicated and that an inter-disciplinary review team be fully engaged in the development and analysis of those objectives. Finally, planning for any stream or meadow restoration project should include an appropriate monitoring program to assess whether the specific objectives stated for the project were achieved.

## A Brief Summary of the Effects Discussions

- A multitude of benefits are associated with restoring floodplain connection and returning the meadow water table to historic condition, including reduced stream bank erosion and improved riparian vegetation and forage. Stream temperature is improved due to deeper base flows, improved shading, and increased ground water interaction. Base flow through shallow ponds may cause detrimental stream temperature effects.
- Fencing is typically necessary to exclude grazing from completed projects, at least in the short term.
- When floodplain function is restored, a portion of winter and spring runoff is stored in meadow soils rather than racing down the pre-project gully during the runoff season. Data indicates that release of this stored runoff results in increased stream flow in late spring. Conversion of dryland vegetation to riparian species more similar to historic condition results in increased evapotranspiration, which may result in lower base flow within the project reach in late summer and early fall. Flow timing effects will vary substantially from meadow to meadow and more data is necessary to better predict effects.
- The pond-and-plug treatment spreads large flows across the floodplain, delaying delivery of the flow to the downstream end of the meadow, and generally resulting in a reduction of peak flood flows. However, this is a highly simplified description of the primary peak flood effect. The overall effect is significantly influenced by several complex factors and will vary for different project sites.
- The pond-and-plug treatment is typically beneficial to native fish, bird, and terrestrial wildlife populations due to improved water quality, soil moisture and riparian vegetation.
- The introduction of ponds into meadows potentially represents both positive and/or negative effects. A foremost concern is proliferation of non-native aquatic species such as bullfrogs that could present a severe adverse effect to sensitive frog species such as the Mountain Yellow-Legged Frog. Proliferation of bullfrog populations has been observed at a few pond-and-plug projects.

- Typical measures to protect sensitive plants and prevent introduction of invasive plants are critical for pond-and-plug projects.
- Pond-and-plug projects have resulted in increased identification of historical heritage sites. Reduced stream bank erosion has protected some archaeological sites.

## Design Considerations

This paper is not intended to be a technical guide for how to design pond-and-plug projects. Design considerations are presented in this paper in very basic terms, with the intention that readers who are resource professionals but not hydrologists or engineers can gain a better understanding of how the treatment works. Recent hydrologic concerns regarding viability of the treatment have focused on project grade control structures, risks associated with flow over the plugs, risks associated with steeper meadow systems, and viability of projects during large floods like a 100-year event.

- Grade control structures are rock and soil structures with riparian vegetation transplants that are typically necessary to stabilize the downstream terminus of pond-and-plug projects. Recent designs have improved substantially from earlier projects constructed in the mid-1990s. Grade control structures must be placed at locations in which the landscape naturally funnels all flows, including large floods, over the structure. The largest floods to test these structures occurred in 2006 (estimated flood return intervals of 5 to 15 years) with good results.
- Pond-and-plug designs generally assume that base flow could, and likely will, at some time leave the designed low flow channel and flow somewhere else on the floodplain, potentially over plugs. Vegetation established on plugs is key to keeping the plug surface stable and capable of resisting shear stresses associated with flood flows. Beaver may also help to maintain the surface of plugs and the base level of pond-and-plug projects.
- A significant test of plugs located within the floodplain occurred on the Big Meadows project on the Sequoia NF, which in October 2009 was subjected to a flood with an estimated 50- to 100-year return interval. Post-flood observations indicated that all project plugs sustained some overland flow, some to depths of 2 feet. However, no significant erosion was observed on any of the plug surfaces
- Steeper meadows present more challenging sites for implementation of pond-and-plug due to the potential for increased flow stresses on plugs and larger sediment sizes and loads generally associated with steeper stream systems.

Assessment of the hydrologic success of any restoration project, including pond-and-plug projects, should include a definition of what “failure” and “success” mean. Flow that cuts across a plug is not likely a failure if the new path is stable or if the flow can be easily diverted back to a location that is stable in the long-term. A project which loses a number of plugs in a flood and is left in an unstable condition that cannot be repaired without essentially re-doing the treatment is likely a failure. Implementing no treatment and leaving a system to continually degrade, widen, and erode vast amounts of meadow could also be considered a “failure.”

# Introduction

This paper is intended to provide a description of the pond-and-plug treatment, briefly present general treatment effects, and discuss basic design considerations relative to potential risks of the treatment. This paper's audience is intended to be Plumas National Forest (PNF) resource specialists and managers who may or may not be familiar with the technique. A primary goal is to document the Forest's current understanding, across PNF ID-team resource areas, of effects associated with the treatment as well as to point out gaps in our understanding that should be addressed by future monitoring or research. Existing studies and research associated with the treatment are catalogued in this paper's References section. As this body of knowledge grows and our experience with the treatment progresses, this paper should be updated.

While other restoration techniques are occasionally mentioned here for comparison purposes, the goal of this paper is not to provide deciding officials with a comprehensive overview of the advantages and disadvantages of different stream restoration techniques. Rather, the intent is to provide information on only the pond-and-plug treatment, in hopes of aiding resource managers who are unfamiliar with the treatment or would like more information on the treatment. This paper is not intended to be a technical guide for how to design pond-and-plug projects. Design considerations are presented in basic terms, with the intention that readers who are resource professionals but not hydrologists or engineers can gain a better understanding of how the treatment works.

Nowhere has this technique been employed to a greater extent than in the meadows of the Upper Feather River watershed. Implementation of pond-and-plug projects has intensified in recent years, with more than twice as many projects constructed since 2002 than was constructed in the 7 years prior (Appendix A).

Several factors have contributed substantially to these phenomena. First, the pond-and-plug technique results in both reconnection of a stream channel with a functioning floodplain and restoration of a degraded meadow's water table up to its historic level. The restored floodplain facilitates much less flood-flow stress along the restored stream channel than for traditional bank stabilization efforts performed within incised, "gullied" channels, so that stream banks are stabilized with less risk of future maintenance or reconstruction. Restoration of the meadow water table results in re-watering of meadow soils and vegetation, with significant effects throughout the restored floodplain for meadow hydrology, wildlife, and forage. Second, the pond-and-plug technique restores a meadow's natural ability to spread flood flows and induce settling and deposition of high sediment loads delivered from the upper watershed. This is a critical natural function associated with points on the landscape where stream systems covert from steeper, sediment transport reaches to broad floodplain, sediment deposition reaches. This function is especially important for buffering human-induced changes to upper watershed hydrology and sediment supply. Other stream stabilization treatments that are located within the incision of degraded channels typically result in less connection to a working floodplain and do not restore this buffering function or restore it to a much lesser degree than pond-and-plug.

These effects are substantially realized within the first year after construction. Also, since much smaller amounts of large rock and other materials are imported to pond-and-plug projects than for many common bank stabilization methods (such as riprap or boulder vanes), the technique allows restoration practitioners to produce near-immediate effects on much larger reaches of stream and meadow than could be treated in the past. Finally, Upper Feather River meadows, particularly on the drier east side of the watershed, have suffered severe degradation due to human-caused activities over the past 150 years, with several stream systems gullied to depths of 6-12 feet or more, converting the meadows to dry lands with channel banks in a highly erodible state and local vegetation and wildlife communities that are far removed from historic condition. Such severely degraded conditions have encouraged restoration practitioners to treat larger lengths of stream and, at times, to “push the envelope” in applying the pond-and-plug technique to more challenging sites.

Successfully designed and implemented, pond-and-plug restores much of the critical hydrologic function of a meadow system, resulting in numerous ecological benefits. The technique is relatively new. Dramatic improvements have been observed at projects completed to date and reliable project design techniques have continually developed over the past 15 years. However, there is still much to be learned about several aspects of long-term ecological effects and project design elements will continue to evolve, particularly for steeper stream and meadow systems. It is readily apparent that no two pond-and-plug projects are completely alike and each project site has its own nuances and challenges. Each PNF resource specialist involved in planning of these projects can start with the brief, common understanding of the treatment presented here and apply her or his own skills to a site-specific analysis of effects.

## Description of the Pond-and-Plug Treatment

The stream and meadow restoration technique commonly known as “pond-and-plug” was first implemented on the PNF at Big Flat, Cottonwood Creek in 1995. Since then, nearly 30 pond-and-plug projects have been implemented in the Upper Feather River watershed, with roughly half of those involving PNF lands (Appendix A). The vast majority of these projects were designed and implemented by the Feather River Coordinated Resource Management group (CRM). While PNF staff have been involved in review and analysis for all of the projects on PNF land, design and implementation has been led by PNF staff for only a few projects. Additionally, roughly a dozen pond-and-plug projects have been implemented throughout the Sierra, outside of the Upper Feather River watershed.

Briefly described, this restoration technique obliterates an existing, incised (“gullied”) stream channel, typically 3-10 feet deep, and redirects flow to a stable channel that is connected with a broad floodplain during annual peak flow events. The pre-project channel is typically unstable and eroding excessively, with near vertical banks and little or no established streamside vegetation. With flood flows confined to the gully, these incised channels are continually widening in an effort to re-gain an appropriate, functional floodplain. Such channels do not generally recover or stabilize within desirable timeframes because a reasonable floodplain width will not be achieved until much of the gully walls and meadow soils are eroded away. The post-project channel is more stable because, when large flows reach a channel-filling flood depth (known as the bankfull stage), flow accesses the channel’s floodplain and spreads out over a broad area. As a result, flood flows are much shallower and less erosive, stream power and shear stress are significantly reduced, and conditions for streamside vegetation establishment and maintenance are improved.

Pre-project incised channels generally formed due to post-industrial anthropogenic activities such as livestock grazing, channel straightening or relocation, timber harvest, road building, beaver or willow eradication, or other land manipulation activities. To access the historic floodplain, the post-project channel is re-located to the meadow surface elevation. The pre-project incised channel is obliterated by constructing a series of earth plugs. Import of enough material to completely fill in the gully is extremely costly. Instead, the pond-and-plug treatment uses on-site material to obliterate the channel. The gully is widened both upstream and downstream of each plug to provide the borrow material. The first upstream plug raises and diverts stream flow into the new channel, which is most often a historic channel that is a remnant of the days when the stream and meadow were connected. When the base level of the stream is raised, the meadow water table rises and the widened gully areas fill with ground water, resulting in a series of ponds that are as deep as the original gully (Figure 1).

**Figure 1:** Post-project aerial photo of Last Chance Creek (2005). The series of ponds and plugs mark the location of the pre-project gully. The widths of constructed plugs indicate pre-project gully width. Historic remnant channels are used for the base flow channel of the restored system. (Photo: Jim Wilcox)

The term "pond-and-plug," though catchy, is a poor moniker for the treatment because the treatment's primary restorative element is not the series of ponds and plugs but the re-connection of the stream channel with its floodplain. Pond and plug features, though potentially significant to project performance and ecological resources, are simply the method employed for economically filling the existing incised stream channel. This technique was pioneered and demonstrated to PNF and the CRM in the early 1990s by Dave Rosgen, an innovative stream restoration expert who is well-known to federal land management agencies. Rosgen describes this technique of re-establishing the channel on the historic floodplain as "Priority 1," his primary technique to be pursued and evaluated for improvement of incised stream channels because, successfully completed, it would result in hydrologic conditions that more closely resemble historic function than treating within the gully. (Rosgen 1997).

Pond-and-plug or Priority 1 projects can be constructed without any ponds or plugs if the existing channel entrenchment is not large and a large enough borrow site is available nearby to economically fill the old channel completely and allow for re-connection of the stream and floodplain. This method was used on the Humbug-Charles project. However, excavation and haul of dirt is very expensive and, depending upon the size of the gully, import of material from a borrow source that is even just one mile away from the project can increase project costs by several times. One interesting alternative has been utilized on the Stanislaus National Forest whereby the original, vast meadow surface is scraped and used as material to fill the gully. This method would result in a restored floodplain that is lower than the historic floodplain.  Also, since the entire restored floodplain will have been excavated and disturbed, quick establishment of floodplain vegetation would be critical.

## A Brief Aside: The Project Planning Process

This paper is focused on technical aspects of the pond-and-plug treatment and not the process by which the treatment would become a proposed action.  However, several reviewers raised a few important planning considerations associated with pond-and-plug and those considerations are discussed briefly here.

General "dos and don'ts" associated with stream restoration projects apply also to projects in which pond-and-plug is an alternative.  For any stream restoration project, it is important to develop an understanding of the current condition and the factors, both natural and anthropogenic, that have shaped that condition.  Natural stream channels, even those considered to be "stable" or "in equilibrium," are dynamic and evolving, constantly depositing and eroding sediment in response to forces such as climate, basin geology, and upland condition and activities - at degrees that vary widely from watershed to watershed.  In many cases, a reasonable cause and effect relationship exists between an incised, eroding stream channel and past or present land management actions.  However, downcutting and rebuilding of meadows is a natural process in the Sierras and, prior to initiating a restoration project, it should be clear why the project meadow has degraded more quickly than what would occur naturally.

Further, the pond-and-plug technique is not a template treatment that should be automatically considered as the preferred alternative for all broad, alluvial valley situations. Rosgen identifies the pond-and-plug type of treatment (re-connection with historic floodplain) as being the first priority for improvement of incised stream channels due to the reduced risk and multitude of benefits associated with the treatment.  But Rosgen, and all qualified stream restoration practitioners, advocate that sufficient fluvial geomorphology, hydrologic and sediment analysis be performed for each unique project site to determine the viability of applying a pond-and-plug treatment.

Stream restoration actions need to be determined to be appropriate for each situation.  For example, treatments which Rosgen has implemented successfully in the Rocky Mountains may respond very differently in Sierra basins that experience rain-on-snow runoff events and are more geomorphically active.  Physical (e.g., roads, homes) or biological constraints (e.g. amphibian life history needs) may exist which influence how or if a pond-and-plug project could be applied.

Ideally, restoration projects should be part of a strategy to improve the watershed beyond the project site.  Fencing to exclude livestock from stream channels has also been effective in restoring hydrologic function for meadows which are not extremely incised.  Ecological benefits due to stream and meadow restoration are difficult to achieve beyond the scale of the project area.  However, a strategic combination of several cost-effective restoration projects such as pond-and-plug, livestock exclosure fencing, and management changes could result in extension of benefits to the landscape or watershed scale.

Stream and meadow systems are critically important landscape features for a multitude of ecological resources.  For any restoration project, it is imperative that the specific project objectives be clearly communicated and that an inter-disciplinary review team be fully engaged in the development and analysis of those objectives.  The term "meadow restoration" means different things to different resource experts. In the case of pond-and-plug, the chief project elements involve restoration of physical properties, namely re-connection of the meadow stream with its historic floodplain and return of the meadow water table to its historic level. These two elements result in establishment of several ecological conditions that are similar or identical to past conditions. However, to cite one example, while areas of impounded water may have occurred historically on a meadow for periods of time, the introduction of a series of large ponds on the landscape is generally not re-creation of a historic condition. While these ponds may function similarly to the historic floodplain during flood flows and may have several positive effects for non-hydrologic resources, the ponds do have effects for wildlife resources that are not similar to past conditions. The implications of introducing ponds on the landscape will likely vary substantially for different project locations. This example is presented only to illustrate the importance of involving an interdisciplinary team of specialists in project development and analysis.

Finally, planning for any stream or meadow restoration project should include an appropriate monitoring program to assess whether the specific objectives stated for the project were achieved. This monitoring can also be designed and implemented to target specific data gaps in our current understanding of the treatment's effects. Some of these data needs can be ascertained from the effects discussion below. A helpful future Appendix to this paper would list a series of monitoring questions which specialists have identified to target questions about the treatment.

## Treatment Benefits and Impacts, both Theoretical and Demonstrated

Properly designed and implemented, the pond-and-plug technique effectively restores much of the natural hydrologic function of the meadow. Ecologically, montane meadows are very important landscape features, particularly in the Sierra Nevada. All of the restoration benefits described below result directly from the stream and meadow hydrologic system flowing much as it did historically. As stated above, the primary objective of the treatment is to reconnect a stream system with a functioning floodplain. Several of the potential benefits described below stem from the effect of raising the ground water elevation. Ground disturbance and the introduction of ponds could result in adverse ecological impacts.

### Reduced streambank erosion

As described above, the re-location of a channel out of its existing gully and re-connecting it with the floodplain results in much less erosive force during higher flows. Reduced streambank erosion reduces turbidity and the transport and deposition of fine sediments in downstream channels. Rapidly eroding streambanks associated with incised stream channels can result in significant loss of productive land and may impact archaeological sites. Treatment benefits are apparent in photos of pre- and post-project streambank condition for several projects, including the 2006 Red Clover - McReynolds project (Figure 2).

As described above, a historic remnant channel is typically utilized for the post-project channel. Such remnant channels typically have well vegetated banks and appropriate channel dimensions to resist flow stresses. The capacity of these remnant channels is often such that the typical annual peak flood (1 year return interval) will overfill the channel and access the floodplain. If an appropriate remnant channel exists on the meadow, utilization of that channel by the project designer will generally be favored over constructing a new channel to convey low flows. The remnant channels typically evolve to a stable geometry in response to the flow and sediment regime delivered from the upper watershed (Figure 2).

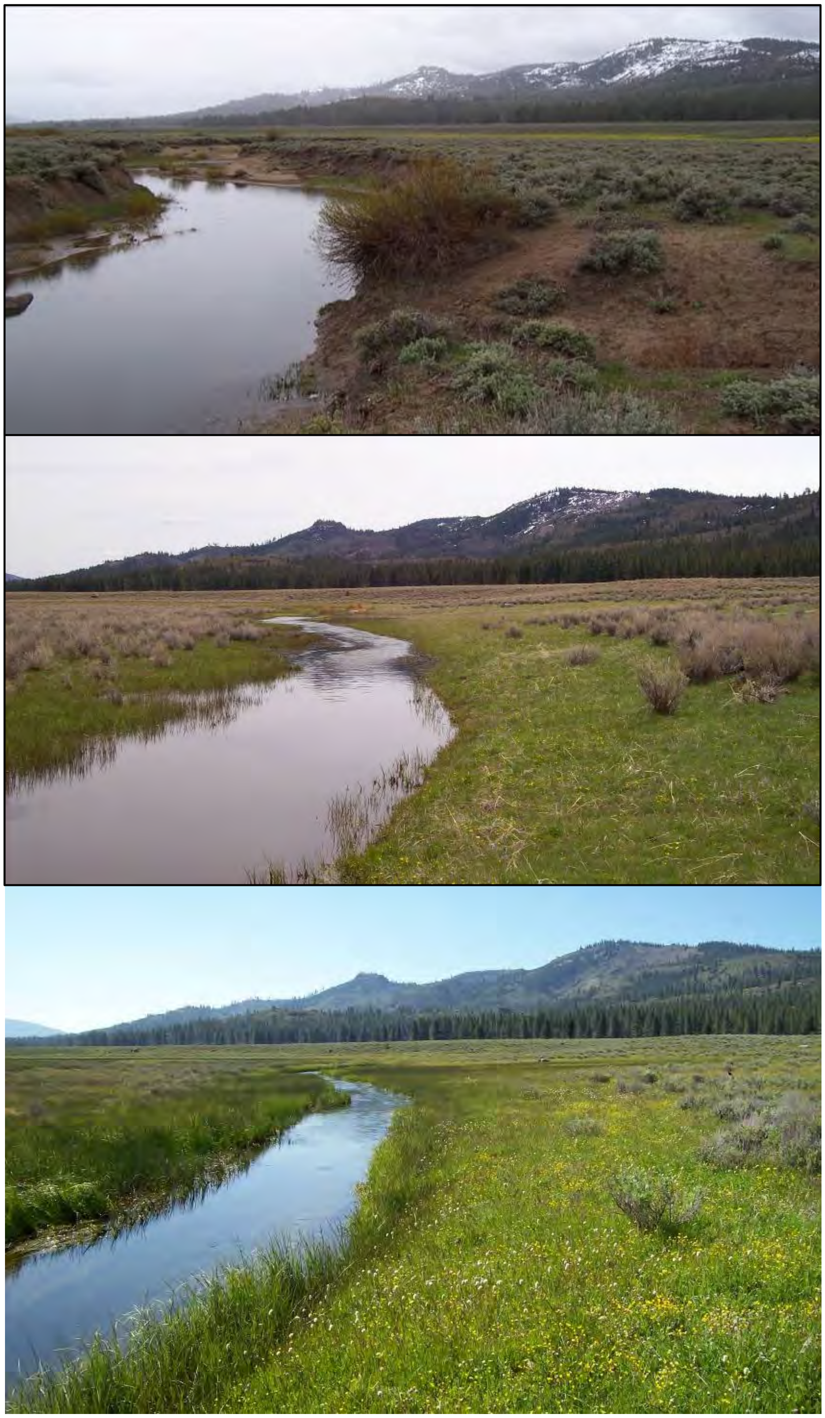


**Figure 2:** Pre- and post-project photos of the 2006 Red Clover–McReynolds Project (2006, 2007 and 2008). The pre-project gully is more than 10 feet deep and 90 feet wide. The steep gully banks are actively eroding. Erosive flood flows for the post-project channel easily access the meadow's broad floodplain, drastically reducing shear stress and resulting in stable stream banks (middle photo, 2007). The bright green vegetation line in the pre-project photo (upper right) is the location of the post-project base flow channel. The bottom photo (2008) shows vigorous riparian vegetation recovery on the channel banks and a narrowing of the channel due to capture of fine sediments. The narrower and deeper channel should result in cooler stream temperatures. (Photos: Jim Wilcox)

In many cases, a remnant channel or a defined base flow channel is not a requirement for application of the treatment. Assessment and observation of meadow floodplains in the Upper Feather River basin indicate that, historically, much of the sediment load from upper watershed streams deposited in alluvial fans with a distributor system of channels that spread onto the meadow surface below. Little or no coarse load material was historically transported to meadow outlets, although fine sediment transport may be an important factor for current or historic meadow channels. When the stream system is re-connected with its historic floodplain, a channel will form (or not) in response to the flow and sediment load that is delivered.

At times, where a usable remnant channel does not exist, it is desirable to pioneer a new channel (e.g. if fishery improvement within the meadow is a project objective). Such channels are designed to have geomorphic characteristics (such as sinuosity, bedload competency and capacity, width / depth ratio, riffle and pool depth, pool spacing) that mimic those of natural channels typical in comparable landscapes. It is important to utilize native vegetation transplants, such as willow stakes and meadow sod mats, to protect the new channel and facilitate the establishment of riparian vegetation.

### Improved forage and riparian vegetation

By raising the stream base level to the historic floodplain elevation, the ground water table is restored. This re-watering of the meadow results in the re-establishment of riparian herbs and woody vegetation. Comparisons of pre- and post-project photos for pond-and-plug projects demonstrate the conversion of acres of meadow vegetation from dry land species, like sagebrush, to riparian species (Figure 3).

pre-project June 2001

August 2002

July 2003

**Figure 3:** The improved riparian grass community and improved livestock forage are evident in this series of photos from the Clarks Creek project. When the meadow is re-watered, the sagebrush quickly dies off.

This conversion has resulted in improved aquatic and terrestrial wildlife habitat and vastly improved forage for livestock grazing. For projects implemented on PNF grazing allotments, typical practice to date has been to provide fencing that excludes grazing for 2-3 years along the restored channel and the obliterated gully. For more sensitive sites, longer-term or permanent fencing may be necessary. For example, if a primary project objective is overhanging banks for fish habitat, then permanent fencing may be required. Fencing protects the restored stream channel and the project plugs while riparian vegetation is re-established. Restored stream channels which utilize historic remnant channels typically see a return of vigorous riparian vegetation within 1-2 years (Figure 2), but the banks of these channels remain sensitive to the types of excessive hoof traffic that may have initiated or widened the meadow gully. Since plugs are newly constructed features with no initial vegetation apart from project transplants, those features usually need more time to establish dense vegetation than remnant channels, particularly plugs with a finished grade that is one foot or more above the water table.

Rather than relying on a general rule for how long livestock should be excluded (e.g. 2 or 3 years), site specific analysis of vegetation along a stream channel's "greenline" (most often, at or slightly below bankfull stage) would likely give a better indication of whether vegetation is adequate to hold stream banks together (Winward 2000). Winward has developed "stability classes" for riparian plants (a rating from 1 to 10 with 10 being as stable as a stream bank composed of anchored rock) and a method for surveying a channel's greenline and calculating its stability rating based on the greenline's composition of species.

Raising the water table could affect some Forest Service-designated "sensitive" plants that have thrived under the drier pre-project condition. Historically, many meadows on the eastside of the Plumas likely had a mix of wet meadow areas and higher dry sites (mounds) that could have supported species such as *Ivesia sericoleuca* and *Pyrrocoma lucida*. These species can be found in drier sites, but most often are associated with habitats that have seasonally wet and dry conditions such as likely occurred historically throughout eastside meadows and flats. Any restoration project that affects the water table and results in long-term saturation of areas that were drier under the pre-project condition could restrict habitat for one or more sensitive plant species, regardless of whether those plants were present historically or not. Site-specific project analysis would determine whether those habitat effects would result in significant impacts to sensitive plant species.

## Timing of stream flow

By raising the stream base level to floodplain elevation, the meadow's historic function of acting as a "sponge" and reservoir for runoff is restored. For the pre-project entrenchment, response to large flows is unfavorable because most floods greater than bankfull are not spread over a floodplain and do not soak into meadow soils. When floodplain function is restored, a portion of winter and spring runoff is stored in meadow soils where it is available for release later in the spring and summer. This restored meadow function results in some level of improvement of flow timing, including augmentation of some seasonal flows, potentially resulting in benefits for aquatic species and downstream irrigators. The primary flow augmentation effect would typically occur in late spring as stored groundwater from winter and spring runoff flows out of meadow soils to the stream channel. The channel flow augmentation effect often extends into summer months but this effect is variable from site to site. Increased post-project evapotranspiration could result in reduced base flow within the project reach during late summer.

The potential stream flow timing benefit is indicated by CRM monitoring results for completed projects. Stream flow was measured in 2006 above and below the Big Flat project on Cottonwood Creek (completed in 1995) (Figure 4). The flow gages are located less than half a mile apart and no significant tributary channels exist between the gages. The data indicates reduced flow peaks below the pond and plug reach. A more detailed look at flood flow recession in May - June 2006 demonstrates that flow downstream of the project, which was lower during flood peaks, is higher than flow upstream of the project as seasonal flow approaches base flow. A similar flow data comparison for the pre-project, degraded meadow is not available. Researchers in the Lake Tahoe Basin used a similar, two-gage approach to study flow timing effects (Tague 2008). The Trout Creek project was constructed in 2001, with one objective being to reestablish hydrologic connectivity between the degraded stream channel and its former floodplain. Comparisons of USGS gages located just upstream and downstream of the project indicated statistically significant increases in flow during snowmelt recession months and a 24% increase for the month of July. For the Trout Creek study, this effect of groundwater storage supporting base flow diminished through the late summer and early fall months but still appeared to be enough to cancel increased evapotranspiration from riparian vegetation along the channel and on the floodplain.

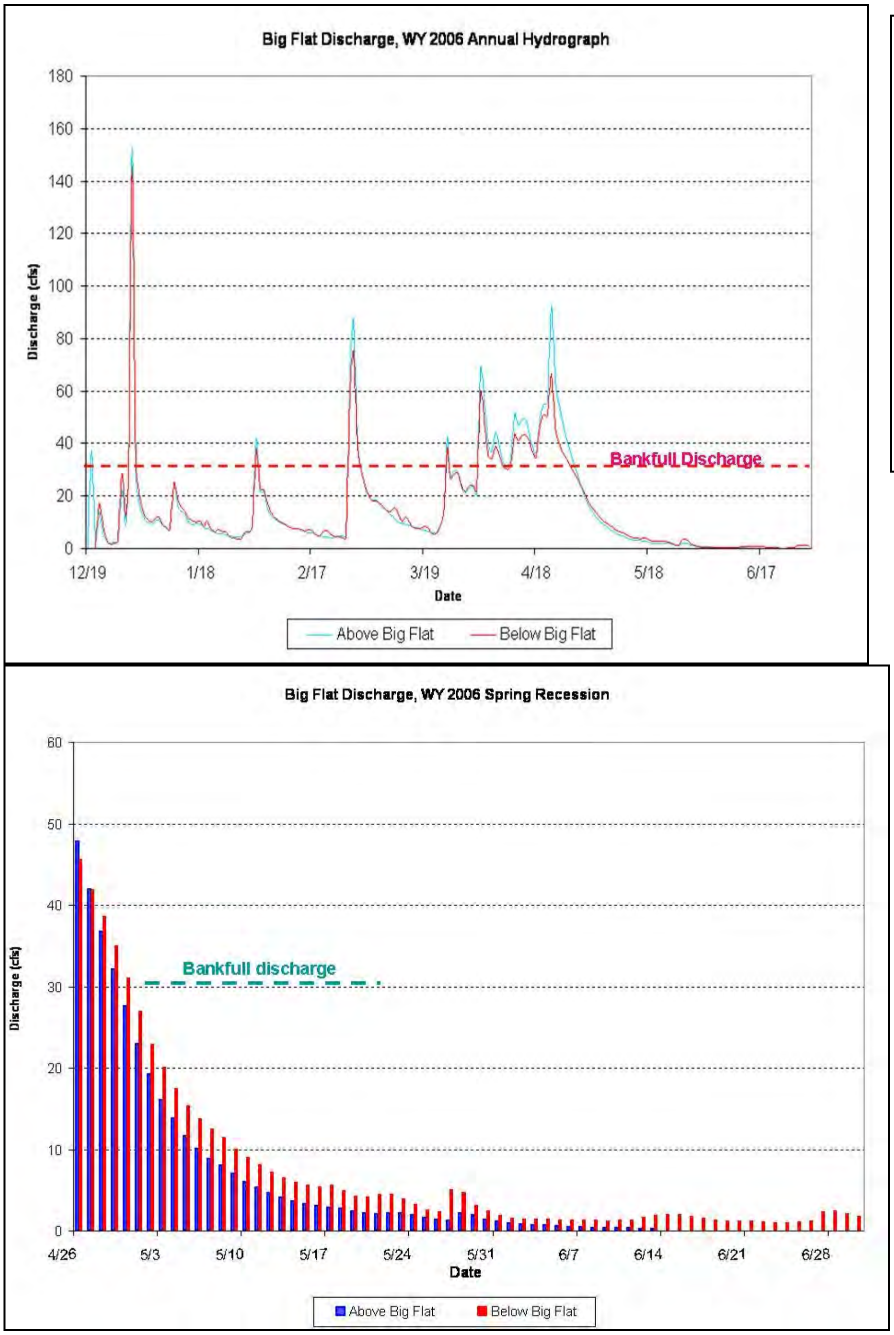


**Figure 4:** Stream flow measurements taken simultaneously above and below the Big Flat project demonstrate reduced flood flow peaks. The lower chart is a closer look at the spring runoff recession and demonstrates that flow downstream of the project is higher through the early part of baseflow season.

For the Clarks Creek project, water table elevations recorded from a ground water monitoring well located within the restored meadow demonstrate that runoff is stored in the meadow. The pre-project water table elevation maximized within 1 foot of the meadow surface but drained to the gully quickly, dropping to less than 2 feet below meadow surface within about 2 months (Figure 5). Post-project data for three different runoff seasons demonstrate that the ground water table elevation remains within 4 inches of the surface for over 5 months each year, even during years that had less than 80% of average precipitation. Further, the drop in water table elevation through the summer months (like Cottonwood Creek, Clarks Creek is not a perennial stream within the project reach) indicates that this stored water is being released downstream during months when, pre-project, it had been unavailable for irrigators and aquatic species.

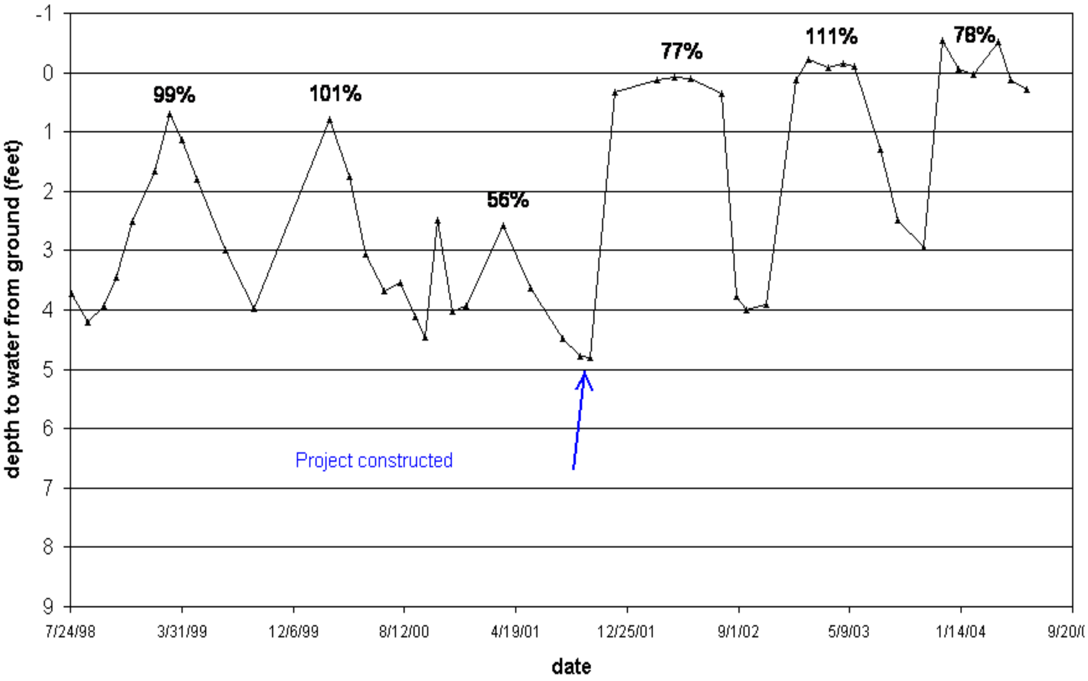


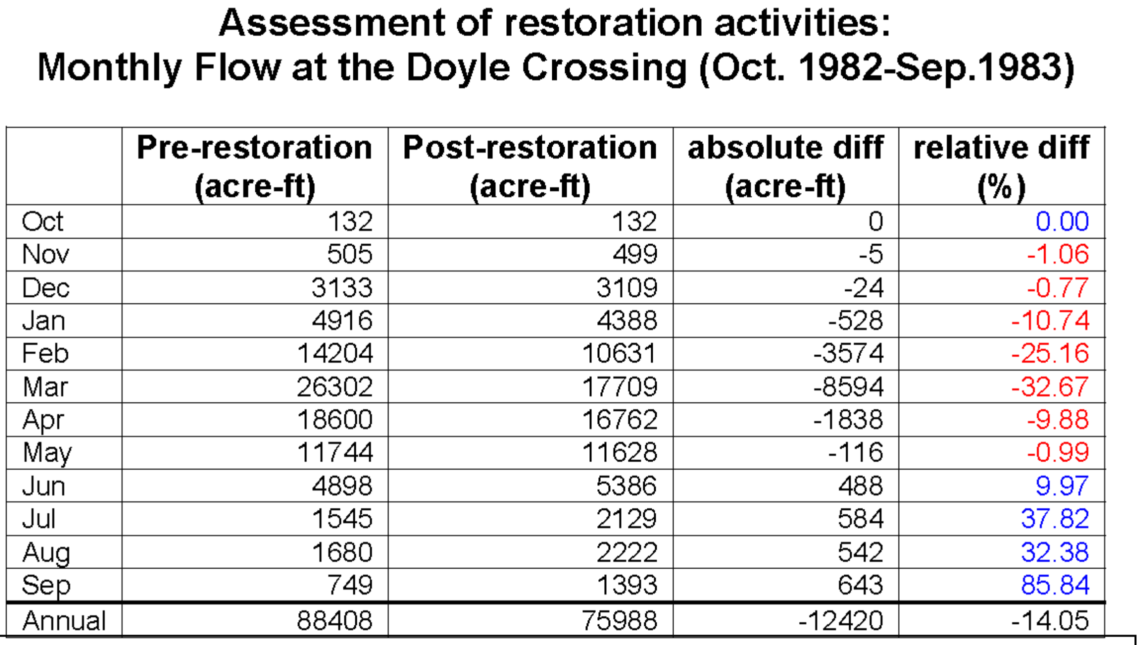
**Figure 5:** Water table levels at Clarks Creek project. Stated percentages represent the amount of precipitation received that year in relation to the annual average.

Sacramento State researchers estimated that, for the 116-acre Clarks Creek meadow, groundwater storage decreased by approximately 65% through summer 2007 (from 218 acre-ft to 76 acre-ft), primarily due to groundwater flowing to the incised, unrestored channel at the downstream end of the meadow (Cornwell, 2008a). The Forest Service Regional Office has secured a grant with National Fish and Wildlife Foundation to estimate improvements in groundwater storage that could be achieved through a region-wide meadow restoration initiative for National Forests in the Sierra Nevada. Those estimates will be completed by 2012.

Using the Last Chance Creek project area as his model site, a UC-Davis professor developed the Watershed Environmental Hydrology (WEHY) model to account for the various hydrologic processes associated with natural landscapes (Kavvas 2004). This model was applied to Last Chance Creek above Doyle Crossing by inputting precipitation data for October 1982 – September 1983 (Figure 6) (Kavvas 2005). The scale of this modeling effort (a watershed area of roughly 100 sq. mi.) is much larger than the scale of the other project-level monitoring or modeling presented in this section. Total predicted runoff for March 1983 for a modeled landscape that was completely restored above Doyle Crossing was 33% less than for the existing, un-restored landscape. The model results presented in Figure 6 represent changes in groundwater storage and flow volumes for the first year after restoration. In modeling flows for a dry month, total predicted flow for September 1983 for the restored stream systems was 86% greater than for the existing, un-restored landscape. These model results include evapotranspiration effects and indicate significant flow timing benefits for pond-and-plug restoration projects in the form of attenuated spring runoff and improved summer base flows.

In assessing potential benefits for stream flow timing, it is important to consider and analyze evaporation and transpiration effects. Restoration of meadow function should result in increased transpiration of groundwater since the landscape is converted from dry land species like sagebrush to historic riparian species. Potential for evaporation of ground water is increased by the installation of ponded water in the restored meadow. Stanford University professors developed an evapotranspiration (ET) mapping algorithm and showed that daily ET for two reaches of restored Last Chance Creek was approximately twice the daily ET for similar degraded reaches that had not been restored (Loheide 2005). CRM flow monitoring data for the 2006 Red Clover / McReynolds Project indicates marked reductions in late season flow at the immediate downstream terminus of the project when compared with flow measured upstream of the project (Feather River CRM, 2010). Pre-project monitoring measured flows of 1.1 and 1.6 cfs at the downstream end of the project reach in August and September 2005, reduced from 1.4 and 1.8 cfs (respectively) measured above the reach. Monitoring for August and September 2008 and 2009 indicated similar flow at the upstream location (a mean of 1.4 cfs) but practically zero flow at the downstream project terminus. The 2009 project monitoring report states that the project's effect on late season base flow cannot yet be fully evaluated because 2007-2009 were droughty years and the meadow's groundwater storage capacity is still filling. However, the report also identifies that at least part of the late season flow reduction within the project reach is due to increased evapotranspiration. As more years of post-project streamflow data is collected, this effect will be better characterized.

Researchers at UC-Davis applied a hydrologic model to a pond-and-plug project in northern California and predicted that summer baseflow duration was actually reduced following the project, with roughly half of that decrease due to an increase in evapotranspiration (Hammersmark 2008). The Bear Creek project was constructed in 1999 on a 2.2-mile-long tributary of the Fall River, approximately 60 miles northeast of Redding, CA. Model simulations demonstrated that the pond-and-plug project decidedly met the project goal of restoring connectivity between Bear Creek and its floodplain. Floodwater storage on the floodplain acted to attenuate peak flood flows (see section D below). However, anticipated improvements in aquatic habitat due to increases in baseflow were not predicted by the model. Model results indicated a decrease in the total amount of runoff of 1-2% and a shortening of the baseflow season (Bear Creek is not a perennial stream) by 13 days. In addition to ET effects, the baseflow decrease was attributed to an increased loss of stored runoff as groundwater that would have drained to the incised channel pre-project stayed as groundwater in the post-project condition and flowed out of the meadow downstream as either shallow groundwater or overland flow.



**Assessment of restoration activities:**
**Monthly Flow at the Doyle Crossing (Oct. 1982-Sep.1983)**

| | Pre-restoration (acre-ft) | Post-restoration (acre-ft) | absolute diff (acre-ft) | relative diff (%) |
|---|---|---|---|---|
| Oct | 132 | 132 | 0 | 0.00 |
| Nov | 505 | 499 | -5 | -1.06 |
| Dec | 3133 | 3109 | -24 | -0.77 |
| Jan | 4916 | 4388 | -528 | -10.74 |
| Feb | 14204 | 10631 | -3574 | -25.16 |
| Mar | 26302 | 17709 | -8594 | -32.67 |
| Apr | 18600 | 16762 | -1838 | -9.88 |
| May | 11744 | 11628 | -116 | -0.99 |
| Jun | 4898 | 5386 | 488 | 9.97 |
| Jul | 1545 | 2129 | 584 | 37.82 |
| Aug | 1680 | 2222 | 542 | 32.38 |
| Sep | 749 | 1393 | 643 | 85.84 |
| Annual | 88408 | 75988 | -12420 | -14.05 |

**Figure 6:** Monthly total flow estimates as predicted by the WEHY model, comparing the Last Chance Creek watershed under restored and non-restored condition. Total predicted runoff for March is 33% less with restoration. Improved base flow conditions following restoration are indicated by substantially higher modeled runoff for summer months (July – September).

The Hammersmark study illustrates that, for all pond-and-plug projects, base flow increases are more likely to be observed downstream of the project area than within the restored reach. Much of the stratigraphy of the Bear Creek meadow consists of a high-permeability layer of alluvial sand and gravel, which Hammersmark modeled as having a permeability of 0.045 m / sec. Apart from ET effects, the shortening of base flow season is also attributable to this exceptionally rapid flow rate of groundwater through the meadow soils. This effect, though less pronounced in typical meadow soils of lower permeability, has been observed qualitatively by CRM staff at several completed projects. The pond-and-plug treatment results in substantial storage of runoff as groundwater in the restored reach. This groundwater is either utilized by meadow plants (transpiration) or released down gradient throughout the spring and summer months but the released groundwater may flow subsurface for hundreds or thousands of feet below the project before interacting with a surface water channel.

More monitoring and investigation is necessary to better predict the effects of evapotranspiration and meadow storage of water in relation to stream flow timing. Flow timing effects will vary from project to project, depending upon several site-specific attributes. Flow timing effects due to pond-and-plug could represent a benefit or impact, depending upon the season and the beneficial use identified (e.g. augmented low flows in late spring may benefit irrigators, potentially lower baseflow within the project reach in late summer could impact fisheries). Perhaps the effect should be primarily characterized as establishment of a flow timing regime that is much closer to the historic regime than the pre-project condition, with meadow and riparian vegetation communities that are also much more similar to historic condition.

## Flood Attenuation

At first glance, potential benefits to the timing of stream flow, as described above, would seem to logically lead to the premise that the pond-and-plug treatment could reduce peak flood flows via the same natural "sponge" function of meadows, since post-project flood flows could soak into meadow soils and would not be left to race down the pre-project gully.

In fact, flood flow at a pond-and-plug project is affected more by the spreading of flow across the floodplain than by the soaking of water into pore spaces of meadow soils. By re-connecting the floodplain, runoff would certainly be attenuated if meadow soil pore spaces were dry. However, large peak flows would most likely occur at a time when the floodplain landscape would have been saturated under both the pre- and post-project conditions. In such cases, since water is not stored within the meadow, the post-project peak flow and the pre-project peak flow would theoretically be identical because the flow into the system must equal the flow out of the system (the "continuity" equation). Post-project flow would be more shallow and slow (due to the roughness of the floodplain) but would occupy more cross-sectional area across the broad floodplain than the fast flow confined to a gully in the pre-project condition.

However, flow rate out of the project area would be identical to pre-project flood flow only after the water that is spread across the floodplain fully regains its downstream momentum. As a result of the pond-and-plug project, flow is spread in a direction away from the more direct, down-valley vector of the pre-project entrenchment, delaying delivery of the flow to the downstream end of the meadow, and resulting in a flood attenuation benefit. For severely incised pre-project channels, the deep gully would not be present post-project to laterally drain meadow soils, which may also reduce flood peaks downstream. Realize that these are highly simplified descriptions of the primary peak flood effects associated with the pond-and-plug treatment. Effects are significantly influenced by several other complex, site-specific factors for projects on the ground.

The flood spreading effect is reflected in the reduced 2006 flood peaks at Big Flat, as presented in Figure 4. The Bear Creek project researchers (see section C above) also modeled a significant flood attenuation effect at the base of the restored meadow (Hammersmark 2008). For the largest flood events simulated (between 2- and 5-year return interval flood flows), peak flow values were reduced by up to 25% due to floodwater storage on the floodplain. Such delays in flood timing, if put into effect over a large scale by several projects such as pond and plug and exclosure fencing that would restore floodplain connectivity, could result in a measurable flood control benefit. Flood-peak reductions for very large, infrequent floods are likely to be less dramatic than for higher-frequency, lower-magnitude flood flows (Hammersmark 2008). Sacramento State researchers described the flood attenuation properties of the Clarks Creek meadow but did not quantitatively predict effects (Cornwell 2008b).

Flood flow effects for a project are dependent upon several site-specific characteristics. For instance, several severely incised channels in the Upper Feather watershed still maintain floodplain connectivity at extremely high flows. For such a channel, extreme flows would be spread across the floodplain in both the pre- and post-project condition so the flood attenuation effect, while still beneficial for smaller floods, may not be as pronounced for extreme flows. Further, once a flow leaves its channel, flood timing and peak are certainly influenced by valley form such as how much the valley outlet constricts flows on the floodplain for both the pre- and post-project conditions.

The pond-and-plug treatment will affect the peaks of most flood flows at the project level, which could cumulatively result in a flood control benefit for downstream landowners and municipalities. However, given inherent variations in precipitation and flow timing characteristics that exist over large watersheds, general predictions of the degree at which flood timing and peak magnitude are affected at this larger scale are difficult to make. Re-connection of a stream channel with a broad floodplain would, however, result in flood response that is much closer to the historic condition.

## Temperature Effects

Most pre-project stream channels are classified under the Rosgen system as “F” channels (Rosgen 1994). These channels have evolved in an incision that has finished down-cutting (often in response to anthropogenic activities) to a stream that is now widening into soft meadow soils to re-gain the valley width necessary to hold a stable channel. Essentially, flow processes are pushing these channels to build a functioning floodplain within the gully floor at an elevation that is 3-10 feet below the historic meadow elevation. Livestock grazing and watering along such channels can further accelerate bank erosion and channel widening.

**Figure 7:** Pre- and post- project photos of Ward Creek (1999 and 2005) indicate stream temperature benefits associated with improved riparian vegetation and shading. (Photos: Jim Wilcox)

Such widening “F” channels have high width / depth ratios. During the low flows that typically exist most of the year, such channels are overly wide and shallow, possessing relatively large flow surface area that subjects the stream to more solar radiation and higher stream temperatures (particularly, of course, during summer months when coldwater aquatic species are most stressed). The lack of shade from streamside vegetation on eroding banks further exacerbates stream temperature impacts.

Post-project stream channels, whether historic remnant channels or constructed pioneer channels, are designed to have width / depth ratios that are consistent with the natural geomorphology of the landscape. Channels are narrower and deeper, contributing to cooler stream temperatures (Figure 2). Re-established and stable streamside vegetation provides shading to further lower stream temperatures (Figure 7). Temperatures for water near the surface of post-project ponds are usually elevated due to solar exposure but deeper water in ponds can provide quality trout habitat year-round.

Apart from solar radiation effects, the raised water table that results from the pond-and-plug treatment may provide benefits to stream temperature by enhancing surface and ground water interaction. During warm periods, groundwater input to streams lowers stream temperature and buffers diurnal stream temperature variations. During the coldest winter months, groundwater input would mollify extremely cold surface water temperatures. The change in magnitude of groundwater flow to a surface stream resulting from a pond-and-plug treatment would vary both seasonally, as stored runoff is either released to the stream or to the air via evapotranspiration, as well as spatially from reach to reach. Stanford University professors used high-resolution infrared imagery and instream temperature measurements to quantify detailed spatial patterns of groundwater recharge to the restored reach at Big Flat (Loheide 2006). Their investigations led to an estimate that maximum stream temperatures could be reduced by more than 3 degrees C through pond-and-plug restoration.

Quantifying stream temperature effects for pond-and-plug projects via empirical data is difficult due to the array of variables that affect stream temperature and the spatial, annual, and seasonal variations of these elements. Most prominent of these confounding variables are flow rate and ambient air temperature, both of which vary profoundly from year-to-year while air temperature can vary substantially from day-to-day.

Recent results from CRM monitoring and informal citizen monitoring on the Smith Creek project, constructed in 2007, indicate that shallow ponds connected to the base flow channel can result in increased stream temperatures. While the ponded areas used to obliterate the gully typically are connected to surface water flow only during flood events, pond-and-plug designs oftentimes use the ponds as a stable and convenient location to cross the low flow channel from one side of the valley to the other, thus following the natural flow path of the valley. At Smith Creek, monitoring data indicates water temperature increases several degrees F as it flows through a single, shallow pond. This effect may also stem in part from less deep groundwater interaction at this project site than at other projects. CRM designers are currently adapting design methods to consider a cold-flow channel from the inlet to the outlet for ponds that are less than roughly 3 feet deep.

## Heritage Resource Effects

The majority of the pond and plug projects constructed to date are in areas that are considered prehistorically and historically significant. Consequently, since 2001, over 80 heritage sites have been recorded for the first time as a result of these projects. Additionally, at least 41 heritage sites have been re-recorded or re-visited.

A Programmatic Agreement exists between the Forest Service, Region 5, the California State Historic Preservation Officer, and the Advisory Council on Historic Preservation. When Forest activities are implemented in accordance with the stipulations of this agreement, the Forest's responsibilities for compliance with Section 106 of the National Historic Preservation Act are satisfied. Section 106 requirements have generally been met on pond-and-plug projects by using the "flag-and-avoid" technique to protect identified heritage resources.

All archaeological sites within the Area of Potential Effect (APE) must be taken into account. If a no effect determination cannot be reached, Section 106 evaluations are required for heritage sites located within the APE for the pond-and-plug project. The APE includes areas of restored groundwater levels, even if no physical impact will occur. To date, the CRM projects have resulted in the evaluations of portions of two large railroad systems which are located on both public and private lands: the Clover Valley Lumber Company Railroad and the California Fruit Exchange Railroad, both of which were recommended as eligible to the National Register of Historic Places. In addition, 12 prehistoric sites have been evaluated in the Last Chance Creek meadow system, Red Clover Valley, and Humbug Valley. Site excavations have contributed geochemical data and, at times, Carbon-14 dating data, which further contribute to our archaeological understanding by providing relative dates to the occupation of the site.

A unique archaeological benefit of the meadow projects is restoration of much of the natural environment of the heritage sites. This provides archaeologists with a clearer picture of the site's natural setting during prehistoric times, and aids our understanding of the site's function and interpretation. Before restoration, the sites appear to be located in exposed, sagebrush zones. Following restoration, the sites are more functionally situated in or near a lush meadow system with access to waterfowl, fish, and cultural material. In several cases, restoration has halted artifact loss and site erosion of prehistoric sites located along degraded stream channels.

The CRM has consistently designated Supplemental Survey Areas (non-APE) in high sensitivity areas (Last Chance Creek, Red Clover Valley, and Humbug Valley) in order to gather a greater understanding of the resource. This is in keeping with its stated mission statement of Coordinated Resource Management. The use of Supplemental Survey Areas has resulted in the recording of heritage sites which otherwise would have been unrecorded.

The pond-and-plug projects have the written support of Native American groups and Tribes, who have been active participants in consultation, review, and in some cases, survey. Restoring the natural environment is a stated tribal priority. Most of the CRM archaeology has taken place on private land, in locations where heritage sites would otherwise have remained unrecorded and therefore potentially unprotected. These projects have been requested by the private landowners due to their concern about meadow degradation. The landowners have actively expressed support for the archaeological component and some have taken steps to protect identified resources on a long-term basis.

## Wildlife Effects

Restoration of the hydrologic function of a montane meadow system should result in significant benefits to aquatic and terrestrial wildlife. Riparian areas are known to be highly productive habitats and ecotones for both aquatic and terrestrial wildlife (Thomas, et al 1978). More than 225 species of birds, mammals, reptiles, and amphibians depend on California's riparian habitats (RHJV 2004). Specifically, healthy meadows are biodiversity hotspots in the Sierra Nevada, providing forage and critical habitat for a wide range of plant and animal species, including many listed species such as the willow flycatcher, great gray owl, and the Yosemite toad (NFWF 2010).

As described earlier, degraded meadow streams have wide, shallow channels that capture higher amounts of solar radiation, and therefore have higher temperatures than streams that are narrower and deeper. Additionally, degraded streams typically lack stream vegetation and shade, so temperatures are further increased. Pond-and-plug designs result in stream channels where vegetation and shade are at or near historic conditions, and this, in combination with channel morphology improvement and increased interaction with ground water, results in lower stream temperatures. While the restored water table will result in higher evapo-transpiration rates that may reduce stream flows within the project reach late in the season, this change represents restoration of meadow and riparian vegetation communities that are similar to historic conditions and a more natural flow regime to which native species are adapted. Restoration of flow and temperature regimes most likely improves habitat connectivity for native species at times for which they are adapted to move.

Meadow restoration likely benefits a wide variety of wildlife species. Meadows are biodiversity hotspots for the animal species of California, particularly birds and amphibians, of which approximately two-thirds depend upon Sierra Nevada habitats (NFWF 2010). Eighty-two terrestrial vertebrate species are considered dependent on riparian and meadow habitat, 24% of which are at risk (Graber 1996). Mountain meadows are key habitats for many animal species because they provide water and shade availability during the three to six month dry season, promote lower summer stream temperatures, higher plant productivity, increased insect prey availability, and special vegetation structures such as willow thickets (Ibid). Examples of species that occur in wet meadows include mule deer, elk, mallard ducks and other waterfowl, yellow-headed and red-winged blackbirds, striped racer, and various frog species (Mayer and Laudenslayer 1988).

Montane meadow habitat is extremely important for birds in the Sierra Nevada; numerous bird species, such as willow flycatcher, depend on montane meadows for breeding habitat and other species, such as great gray owl and red-breasted sapsucker, use meadows as important foraging habitat (Siegel and DeSante 1999). Additionally, montane meadows provide critical molting and pre-migration staging areas for juveniles and adults of a broad array of Sierra landbird species, such as orange-crowned and Nashville warblers, many of which also do not actually use meadow habitat for breeding (Ibid).

Meadow restoration likely benefits native fish populations. The changes to hydrology, channel morphology and water quality described earlier all reflect positive changes to fish habitat. Typically, channels in degraded meadow systems are relatively wider and shallower than non-degraded streams. Additionally, these streams typically lack deep pool and riffle habitat, or stable, undercut banks that are important habitat attributes. Pond-and-plug designs typically restore these features to the channel components of the meadow. The restoration of stable banks to these streams also eliminates a major source of sediment. Fine sediment delivered to streams can impact spawning and incubation (typically early spring for rainbow trout) and increase mortality of eggs and fry. Reduction of sediment from these sources should increase survival.

Fisheries monitoring conducted by the CRM at Big Flat in May 2000 found 60 rainbow trout in a 100-foot reach of Cottonwood Creek; that reach was typically dry and devoid of fish at that time of year (May) in the pre-project condition (Wilcox 2005). The Little Schneider project resulted in restoration of year-long flow during non-drought years so that trout were not stranded in dried-up reaches during those years. Macroinvertebrate monitoring at a 2001 floodplain re-connection project in the Carson River watershed (using a technique similar to pond-and-plug) demonstrated statistically significant improvements in the macroinvertebrate community during the first two years after construction (Herbst 2009). The macroinvertebrate community shifted from being dominated by pollution- (i.e., sediment) and disturbance-tolerant taxa to one comprising more sensitive taxa and more closely resembling the composition found at two nearby, healthy reference streams. Recent, not yet published studies on Trout Creek in the Lake Tahoe Basin indicated improved macroinvertebrate communities in the initial period after restoration but also that the response was not sustained after a period of 5 years (Herbst 2010). This study also points to a need to monitor ecological response to stream restoration over the long term.

Meadows and riparian areas are the single most important habitat for birds in the west; meadow restoration and management should be among the highest priorities for avian managers in the Sierra Nevada (PRBO and USDA). Recent restoration efforts, primarily in the form of removing grazing, have resulted in increases in numerous meadow bird species. Dense patches of willow or alder are a critical habitat feature for meadow dependent birds and tall, lush herbaceous meadow vegetation is important for concealing nests and supporting invertebrates that birds prey upon. Preliminary results of avian monitoring conducted by the CA Department of Water Resources (DWR) at Red Clover – McReynolds (constructed in 2006) indicated 16 additional bird species observed post-project, a 20% increase over the pre-project survey. These additional species include riparian and wetland species such as marsh wren, pied-billed grebe, and Wilson’s phalarope (CA DWR 2007). The DWR surveys also indicated a 64% increase in waterfowl young produced between 2004 and 2007. Many of the species which occurred only post-project are State or federal special status species, including but not limited to bald eagle, black-crowned night heron, and double-crested cormorant. Statistically significant increases in total avian density and species richness were found for a DWR study at the Clarks Creek project (CA DWR 2005).

Human eradication of beaver from PNF meadows is believed to be a key element in the loss of available meadow ecosystems. Beavers naturally perform the same type of work and results that are desired of the pond-and-plug treatment. That is, beavers spread flood flows and can re-water dried meadow systems. The CRM’s pond-and-plug projects are usually designed with the assumption that beaver will occupy and thrive within the restored project reach. During the project planning phase, designers need to assess whether project objectives can be achieved without extensive intervention and construction by encouraging the proliferation or introduction of area beaver populations. Installation of some small raises at channel riffles using rock or large wood may be enough to encourage substantial meadow improvement via beaver.

The presence of ponds in meadows as a result of the pond-and-plug treatment represents both benefits and potential negative effects. Ponds may provide improved habitat for adult trout during seasons of extremely cool or warm temperature and, if located within the floodplain, would be accessible to the rest of the stream system. However, ponds may serve as habitat for non-native species, and, in some cases, may result in temperature increases. The creation of ponds may introduce or increase populations of non-native bullfrogs and bass in these meadows, negatively affecting amphibians. Increased trout populations, though potentially desirable for recreationists or fisheries specialists, are also known to impact amphibian populations. Amphibians of specific concern are the Mountain Yellow Legged Frog (MYLF), which the US Fish and Wildlife Service (USFWS) is expected to imminently list as a Threatened species, the Foothill Yellow-Legged Frog (designated as a Forest Service “sensitive” species), Northwestern Pond Turtle (sensitive), California Red-Legged Frog (Threatened), and Pacific Tree Frog (Management Indicator Species). Therefore, the potential for increases in bass and bullfrog should be assessed and the presence of amphibian species of concern should be considered during project design, balancing the benefits and potential negative effects, including defining mitigation measures.

Ponds created by pond-and-plug efforts typically provide high-quality potential breeding habitat for bass or bullfrogs. Dramatic increases in bullfrog populations have been observed post-project at the Little Schneider Creek, Clarks Creek (PNF) and Carman Creek (Tahoe NF) projects. Bullfrogs existed at Carman Creek pre-project, although no pre-project survey data for bullfrogs are available. Bullfrogs were not known to exist pre-project within the Little Schneider and Clarks project areas, although a population did exist upstream of the Clarks project in a roadside watering pond. A large population of bass currently exists in the ponds at Little Schneider; bass were not known to occupy that area pre-project. These are the only known cases of aquatic invasive introduction or proliferation from pond-and-plug projects in the Upper Feather River watershed. However, little formal monitoring and documentation for invasive aquatic species has been performed to date on pond-and-plug projects. Pre- and post-project monitoring of bass and bullfrogs should occur.

Substantial increases in bullfrog or bass populations would likely present a severe adverse effect to sensitive frog species like the MYLF. Bullfrogs are native to the eastern United States but introduced in the west; both natural and man-made habitats pose a risk for bullfrog invasions. Established populations of bullfrogs are extremely difficult to eradicate, as are fish species such as bass. Bullfrogs are extremely prolific; a single bullfrog may lay in a single clutch, thousands of eggs (Schwalbe in Roach, D. 2004). Adult bullfrogs are voracious, opportunistic predators (Schwalbe and Rosen 1988) that will readily attack any live animal smaller than themselves, including conspecifics and other frogs (Bury and Whelan 1984). Introduced bullfrogs have been implicated in the decline or displacement of many amphibians including foothill yellow-legged frogs (*Rana boylii*; California, Kupferberg 1997) and northern red-legged frogs (*Rana aurora*; Oregon, Kiesecker and Blaustein 1997, 1998). Fisher and Shaffer (1996) found a negative correlation between the presence of introduced exotics (bullfrogs and fishes) and native amphibians in California. However, they did not discriminate between fishes and bullfrogs in their analyses. Because bullfrogs are likely to co-occur with mountain yellow-legged frogs only at lower elevations, the potential for impact is restricted to these portions of the mountain yellow-legged frog's range. In addition to predation, bullfrogs could potentially affect desirable aquatic wildlife species by hosting and supporting proliferation of disease in the aquatic environment, such as the chytrid fungus.

MYLF concerns are usually minimal for pond-and-plug projects proposed at the drier, flatter stream systems typically found on the east side of PNF. However, invasive species are still a policy issue that needs to be addressed, regardless of MYLF presence. For areas that are suitable for MYLF, more pre-project monitoring and investigation is needed to assess the potential for bullfrogs to migrate to or proliferate within a completed pond-and-plug project. Early conferencing with USFWS is necessary for proposed projects in areas suitable for MYLF. Human introduction to the constructed ponds of bullfrog and bass species is more likely for some project sites than others. A recent conference with USFWS regarding proposed restoration for Boulder Creek (Mt Hough RD) indicated that the USFWS felt the potential human introduction of invasives was an unacceptable risk because Boulder Creek has a known population of MYLF. USFWS informally supported the hypothetical notion of implementing a project in an unoccupied drainage parallel to Boulder Creek.

Theoretically, restoration of the historic hydrologic function of a meadow should result in benefits to wildlife populations that naturally reside in that ecosystem. In the case of the MYLF, more investigation is needed to determine which physical features can be incorporated in the pond-and-plug design to improve habitat. Instream habitat for MYLF could potentially be improved but the introduction of ponds would likely not benefit MYLF and may result in indirect impacts. It should also be considered that restoring hydrologic function may increase populations of potentially undesirable non-native fish species, such as largemouth bass or brown trout. Further studies should be completed on how these pond/plug projects affect native fisheries, including water quality (temperature and potential disease), downstream sediment budgets, aquatic connectivity, development of invasive species breeding and rearing habitat, and general habitat requirements. In general, stream restoration projects on PNF lands need to protect and encourage native species while not introducing or causing proliferation of invasive species, as directed in current Forest planning documents (USDA 2004).

## Botanical Effects: Invasive Plant Species

The pond-and-plug restoration technique typically involves significant ground disturbance, particularly in the excavation of pond areas and repeated traffic in hauling material from the pond area to the plug area (hauling is typically performed with a front-end loader). Large quarry rock needed for construction of the project grade control structure (described in section IV below) is usually imported and hauled to the structure site in dump trucks. These activities can result in the introduction of non-native plant and noxious weed species, which can severely impact the area ecology. The disturbed areas provide habitat where invasive plant species can thrive and out-compete native species. Further, any existing infestations of invasive plant species on the project site can be dispersed and exacerbated by construction activities. Particular noxious weed species of concern for riparian restoration projects are Canada Thistle (*Cirsium arvense*) and Tall Whitetop (*Lepidium latifolium*) because these species thrive in wet areas. If introduced, these species are difficult to eradicate because mechanical treatments may prevent seed set but typically do not kill all of a plant’s rhizomes. In most cases, eradication would require chemical treatment (i.e. herbicides).

Typical PNF measures to prevent the introduction of invasive plant species must be implemented on all pond-and-plug projects. These measures include thorough washing of construction equipment prior to bringing equipment on site; the use of native seed mixes for revegetation; and when imported materials, such as quarry rock, mulch and hay/straw, are needed, using only materials that are certified weed-free. Control areas are typically established for areas with known noxious weed occurrences. Traffic and disturbance is excluded from these areas. To establish vegetation on disturbed sites (particularly constructed plugs) CRM projects typically utilize native grass seed that is gathered the previous season from within the project site. Results for these seeded areas have been positive. The native grasses sown in the Upper Last Chance project yielded high rates of germination. No noxious weeds were found in the seeded areas during visits to the site one year after project implementation.

## Carbon Sequestration

Qualitatively, restored meadows appeared to significantly increase organic carbon stocks through the much increased root mass and surface growth associated with conversion of dryland vegetation species to meadow herbs. In 2008, the CRM undertook a project to: 1) establish an acceptable scientific protocol to quantify carbon sequestration in restored versus un-restored meadows; 2) quantify carbon stocks in three restored meadows; and 3) quantify carbon stocks in three un-restored meadows to provide baseline data for future restoration. Initial data analysis indicates that restored meadows contain twice as much total carbon per acre (an additional 40 metric tons per acre) as degraded meadows (Wilcox 2010a).

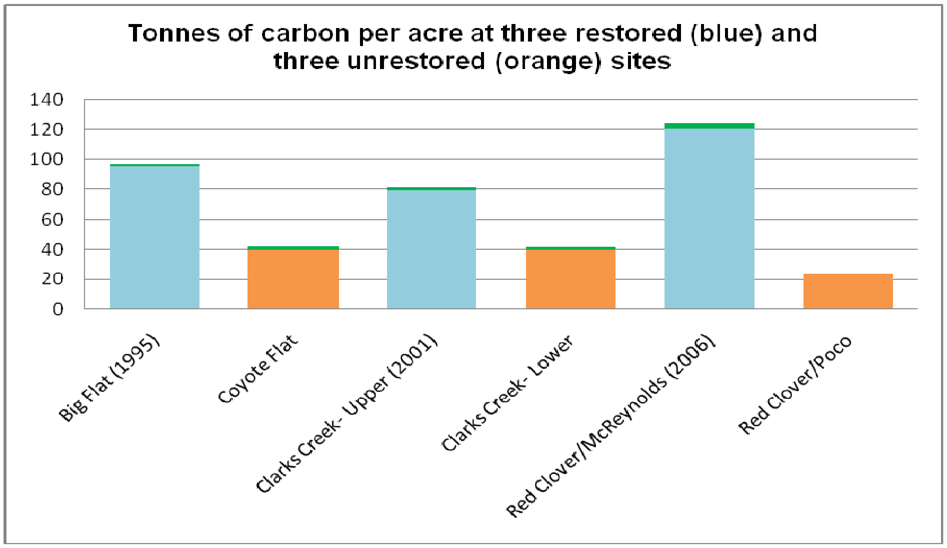


**Figure 8. Metric tons of carbon per acre in each sample meadow. Green at the top of each column represents aboveground biomass carbon.**

The columns in Figure 8 are arranged so that loosely comparable sites are next to each other, with the construction date given for the site treated with pond-and-plug. Big Flat and Coyote Flat are both in the Last Chance drainage, three miles apart from each other. The two Clarks Creek sites are on the same creek, less than one mile from each other. The Red Clover Poco site is two miles downstream of the Red Clover McReynolds site. On average, the restored meadows show a 177% increase in total carbon per acre over the unrestored meadows. Figure 9 demonstrates that the largest difference for carbon occurred below ground within 12 inches of the meadow surface, where most of the carbon is present for both restored and unrestored meadows.

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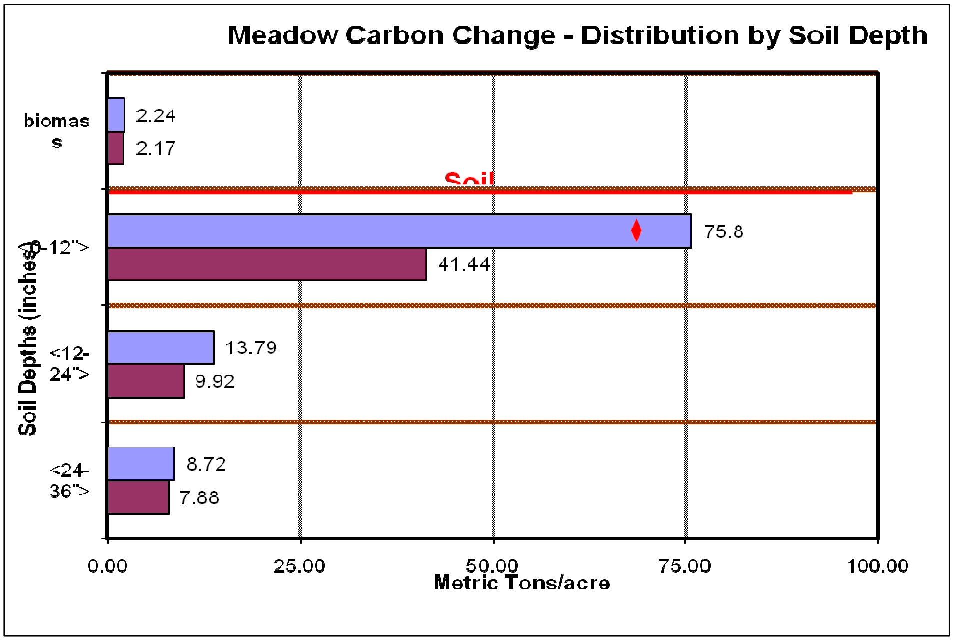

**Figure 9. Total metric tons per acre of carbon in restored (blue) and unrestored (maroon) meadows displayed by depth. The soil surface is shown as a red line.**

## Hydrologic Risks and Design Considerations

Ever since the first pond-and-plug project was proposed on PNF lands, and continually since then, concerns have been raised by PNF specialists and CRM signatories from all disciplines regarding the long-term viability of these projects and the risk of hydrologic "failure." Certainly, such concerns are well-founded for any stream restoration technique because of the challenging expectations that the restored system will remain stable and provide improved habitat under the full range of flow and sediment loading conditions. For example, a design for Red Clover Creek - McReynolds would need to be stable throughout roughly 80% of the calendar year when flows are less than 1 cubic foot per second and also at the instances when the creek is experiencing a 100-year flood of approximately 6000 cfs.

As stated above, pond-and-plug is a relatively new technique within the relatively new field of bio-engineered stream restoration. The CRM and PNF have been among the leaders nationally in pioneering this treatment and we have learned a great deal from the implementation of more than two dozen different pond-and-plug projects.

Excessive erosion and gullying of the pioneered, new channel for the 1995 Big Flat project demonstrated the need to "under-design" rather than "over-design" the new channel so that higher flows will readily access the floodplain and not be confined to the channel to the point where downcutting occurs and is deeper than rooting depths. The Big Flat project also reinforced the approach that new channels should be cut into the meadow only when absolutely necessary and that working with existing meadow features such as remnant channels, or leaving flow to sheet over the meadow where a channel does not exist and is not needed, is preferable to constructing a new channel. Failure of the Willow Creek project demonstrated the importance of constructing an anchoring, grade control structure at a location that is assured of having large flood flows funneled over the structure. Extenuating circumstances limited the CRM to locating the grade control for that project, toward the middle of the meadow reach where flood flows could circumvent the structure. Additionally, the structure for Willow Creek was a version of a step-pool design that is no longer used. Constructed in 1996 less than three months prior to the 1997 flood of record, the step-pool structure failed and re-initiated headcutting. CRM designers have consistently applied adaptive management to pond-and-plug projects, improving design and construction techniques and resulting in recent projects that are much more stable than the two projects discussed in this paragraph, which were constructed nearly 15 years ago.

Most recently, hydrologic concerns voiced have emphasized the viability of grade control structures, risks associated with flow over the plugs, risks associated with steeper meadow systems, and viability of projects during large floods like a 100-year event. These concerns, and design considerations to address such concerns, are briefly described below.

As stated in the introduction, design considerations are presented here in very basic terms, with the intention that readers who are resource professionals but not hydrologists or engineers can gain a better understanding of how the treatment works. This paper is not intended to be a technical guide for how to design pond-and-plug projects. Detailed case studies of the design for one or two specific pond-and-plug projects would provide stream restoration practitioners with better, more comprehensive insight to the design details of this treatment.

Within the stream restoration field, different design philosophies and approaches currently exist so a brief characterization of the approach used to date for pond-and-plug projects may be helpful. In fluvial geomorphology parlance, use of existing remnant channels on the meadow surface would likely be considered an “analog” approach to channel restoration. The designer starts with the assumption that the remnant channel was once stable and will be stable with respect to erosion and sedimentation in the future. Other restoration practitioners may take a more “analytical” approach to design in which hydraulic and sediment transport modeling are used to determine the dimensions of a stable channel system rather than ascertaining those dimensions from a presumed stable, reference channel on or near the project area. Intensive analytical designs can take more time and money to develop, primarily due to extensive sampling and surveying necessary to perform sediment transport modeling or advanced hydraulic modeling. Most stream restoration designs combine these two approaches. A “combination” design approach might include the assumption that the remnant channel will be stable, but that assumption would be verified with hydraulic and sediment transport modeling and field investigations.

To date, the CRM’s “combination” design method could be characterized as closer to an analog approach, with the stability of remnant channels identified within the project area being verified by analytical assessment using basic, industry-standard hydraulic models and qualitative field investigations of sediment transport competence and capacity. These remnant channels are expected to adjust over time to the sediment size and load delivered. More intensive quantitative sediment modeling and advanced hydraulic modeling may be helpful for improving designs and predicting performance, particularly on steeper pond-and-plug projects, as discussed briefly below.

## Grade Control Structure

As described above, by restoring streams to regain connectivity to a broad floodplain, the likelihood of project success is far greater than a restoration treatment that is undertaken within the incised gully of the existing stream system. This position is plainly supported by comparing calculated shear stresses for large flood flows that are spread out over a floodplain versus the much higher stresses developed when those flows are confined to a gully.

When the base level of the stream system is raised to meadow elevation at the first upstream plug, it is common for the stream level to be lowered back to the incised, gullied elevation at the downstream end of the project reach. At that terminus, flows typically need to be dropped 3-10 vertical feet over a structure constructed of rock and soil. This is the point at which the pond-and-plug treatment is most vulnerable. The typical mechanism for potential failure is called an “end run” of the structure, in which a portion of a flood flow finds a soft location off of the armored structure. Once a small nick is formed at this soft location, flow can be concentrated there, eroding the nick deeper. Given enough flow power and duration, the nick can deepen, widen, and lengthen, developing into a gully that diverts the majority of flow around the hardened structure.

To avoid an end-run of the grade control structure, it must be placed at a location in which the landscape naturally funnels all flows, including large floods, over the structure and into the downstream gully. This is the chief design consideration for these structures. Also, the grade control structure needs to be keyed into the gully or funnel walls so that the seam between the hardened structure and the softer wall material does not become a nick point where an end run can start.

Other design considerations include structure slope and shape. For example, the grade control structure for the Three-Corner Meadow project (Tahoe NF) was damaged during the 2006-07 floods due to excessive concentration of flow in the middle of the structure, which was built at a relatively steep slope of 7%-8%. The Three-Corner Meadow grade control structure was subsequently repaired and reconstructed to spread flows better and the slope of the structure was reduced to approximately 5%.

The CRM's design for these structures has changed considerably since earlier projects such as the Willow Creek project. Current grade control structures are built to be long spillways with no more than a 5% slope. The low flow channel is constructed within the spillway to confine base flows to a narrow channel that is fish-passable. The low flow channel meanders over the spillway so that its effective slope is less than 3%-4%. Riffle-pool sequences are built within this channel to dissipate flow energy and to aid fish passage. The structure is built with a soil core that is mixed and armored with a 3-4 ft thick layer of soil and small rock intermingled with large rock (typically 2-3 feet in diameter). Willow and sod transplants are installed on the soil and rock mixture to improve shading and habitat on the structure and to further resist flow erosion. The dense root system of these plants further binds and strengthens the structure.

**Figure 10:** Alkali grade control structure on Last Chance Creek demonstrates the stability of the current design method during a flood in spring 2006. First photo is February 23, 2006, second photo taken on February 28, and third photo in May 2006. Note in the first and third photos that low flows remain in the constructed riffle-pool base flow channel after the flood. (Photos: Jim Wilcox)

Concerns have been raised because these structures have not been tested by a large, 100-year flood. In the Upper Feather River watershed, the largest test flood to date occurred in

2005 – 2006. The floods of that runoff season peaked at calculated return intervals that range from less than 5 years to as much as 15 years, depending upon location in the watershed, and several flood events greater than bankfull occurred that season in the Last Chance Creek watershed. Apart from the Three-Corner Meadow structure, none of the dozen or more pond-and-plug grade control structures that existed at that time received significant flood damage (see Figure 10). During design phase, conventional engineering charts and models for shear stress and channel rip rap sizing can be used to specify large rock of sufficient size to maintain the structure (USACE 1991 and USDoT 1989).

Piping of flow, in which the structure erodes from within due to material being pushed through the face of the grade control structure by pressure from the water surface upstream of the structure, is not a practical concern because the length of these structures, relative to the length of earthen dams, is much greater. Conventional engineering flow net calculations can be used to verify that the length of the spillway is sufficient to prevent piping.

## Flow over the Plugs

A common concern for the long-term stability and integrity of a pond-and-plug project is whether or not the earthen plugs that obliterate the gully are stable. For a typical application of the treatment, the earthen plugs are not considered to be dams because the “head,” i.e. the static water pressure exerted on the plug as measured by the difference in water elevations of the pond immediately upstream and downstream of the plug, is small, ideally less than 0.5 ft to 1.0 ft. Unlike a grade control structure, the downstream face of a plug may not be long and shallow-sloped but is typically abruptly sloped at approximately 30%-70%. However, piping is usually not a concern for these plugs because the head (water pressure) is not large enough to force material through the plug and because most plugs are relatively longer than typical earth dams. Piping could be an issue for plugs on steeper projects (see below).

The integrity of a plug can also be threatened by excessive flows over the plug. As described above, the remnant channel typically conveys low flows over the meadow at a location that is separate from the obliterated gully. However, during flood stages, flow is spread across the entire meadow, including over plugs designed to be part of the floodplain. If a headcut develops on a plug, flow could be concentrated for a long enough duration to divert more flow over the plug and eventually cut through the entire length of the plug (Figure 11).

If flow over a plug were to cause a nick point, that nick would usually occur at the downstream edge of the plug because the flow elevation drops abruptly at this edge, from the elevation of the pond upstream of the plug to the elevation of the downstream pond, potentially resulting in turbulent, erosive force at this edge of the plug during a large flood. The downstream edge of a plug with a small change in flow elevation (less than 0.5 ft to 1.0 ft) will be subjected to less erosive force than a plug with a larger change in base elevation and will thus be less likely to form a headcut. If a plug were to have concentrated flow that eventually cut through the entire plug, the plug immediately upstream would now have its head essentially doubled, placing further stress on that plug.

An abrupt drop at the downstream edge of plugs is susceptible to cutting during flood flows and can be ameliorated by sloping the surface of the plug. Again, this mitigation would be more difficult to achieve on plugs subjected to a larger difference in elevation of adjacent ponds because the slope of the plug surface would be steeper and shear stress due to flow on that steeper slope could be too high. Willow or sedge mat transplants can be added to armor the downstream edge or slope of plugs that are identified to be at risk of cutting due to flood flows.

**Figure 11:** Excessive flow over this plug on Last Chance Creek at Jordan Flat during the 2006 floods caused the base flow to be diverted over the plug. Excessive flow was due to unforeseen dynamics between Last Chance Creek and a tributary stream. A berm was constructed and the problem corrected in 2007. Excessive flow over plugs could headcut through the entire plug, lowering the upstream pond elevation to the elevation of the downstream pond and essentially doubling the head on the next upstream plug. (Photo: Joe Hoffman)

A significant test of the integrity of plugs located within the floodplain during large flows occurred on the Big Meadows project on the Sequoia NF (Wilcox 2010b). Several of the design elements discussed above to reduce risks associated with flood flows on plugs were incorporated in the Big Meadows project (constructed in 2007, Figure 12). In October 2009, the project area was subjected to a high volume, high intensity precipitation event with over 8 inches of rain falling in less than 20 hours. Post-event field observations and stream gage records from the Kings River watershed indicated that flow through the project peaked at approximately 1200 cfs, estimated to be the flood with a 50- to 100-year return interval (i.e. a 1% - 2% chance of occurring in any given year). Post-flood observations indicated that all project plugs sustained some overland flow. Despite flood depths on the plugs of up to 2 feet and estimated flow velocities of up to 3.5 feet per second, no headcut was observed on any plug and very little mobilization of surface soil particles was observed.

Nearly all pond-and-plug designs assume that, due to natural processes, the channel that carries base flow could, and likely will, leave the designed low flow channel and flow somewhere else on the floodplain, potentially over plugs that have been designed to be part of the floodplain. Only in the case where plug surfaces are substantially higher than the restored floodplain is this assumption not made. For example, flow could occur over a plug throughout the year, not only during larger floods, because a beaver dam on the designed base flow channel could divert the base flow. Since base flow location is likely to shift in response to natural processes, stable, well vegetated plug surfaces, particularly at the downstream edge of the plug, are critical for the success of pond-and-plug projects.

**Figure 12:** Big Meadows Pond-and-Plug Project, Sequoia NF. Project was constructed in fall 2007. Photo taken in spring, 2008 during the first runoff season. (Photo: Wayne Luallen)

Beaver may also help to maintain the surface of plugs and the base level of pond-and-plug projects. As an example, the CRM recognized during the design phase for Red Clover - McReynolds (on Goodwin Ranch) that beaver would likely move into the project area, which in fact they did shortly after construction began. The beaver constructed a dam on the low flow, remnant channel, diverting the low flow back toward the obliterated gully and over one of the plugs. In anticipation of this, the CRM designed the difference between all ponds on the project to be less than 6 inches, so that when the low flow was diverted, stresses on the plug would be lower and plug vegetation would eventually keep the new, diverted channel stable. Since the beaver dam described above occurred before the plug was vegetated, flow did cut through the entire plug. However, the beaver apparently were not satisfied with a lower baseflow elevation at this point and fixed the elevation change by damming the new baseflow channel at the cut plug (see Figure 13).

**Figure 13:** At the Red Clover – McReynolds Project, flow had cut through a plug shortly after construction due to damming of the designed base flow channel. Beaver subsequently dammed the cut at the plug so that base flow elevation is maintained upstream of the plug. (Photo: Joe Hoffman)

Vegetation established on plugs is key to keeping the plug surface stable and capable of resisting shear stresses associated with flood flows. To facilitate quicker establishment of vegetation on the newly constructed earthen plugs, mats of native sedges and topsoil excavated from the pond borrow sites have been stockpiled and spread over the surface of the completed plug. CRM monitoring from the past 10 years indicates that seeding of plugs is integral to establishment of vegetation on the plug. In most cases a matted grass surface on a plug would not develop within the first two to three years, and could take up to 5 years to provide coverage that is dense enough to fully resist shear stresses associated with larger flood flows. Transplant or import of sod mats during project implementation can provide a highly-resistant, matted vegetative surface on the plug within the first year after construction.

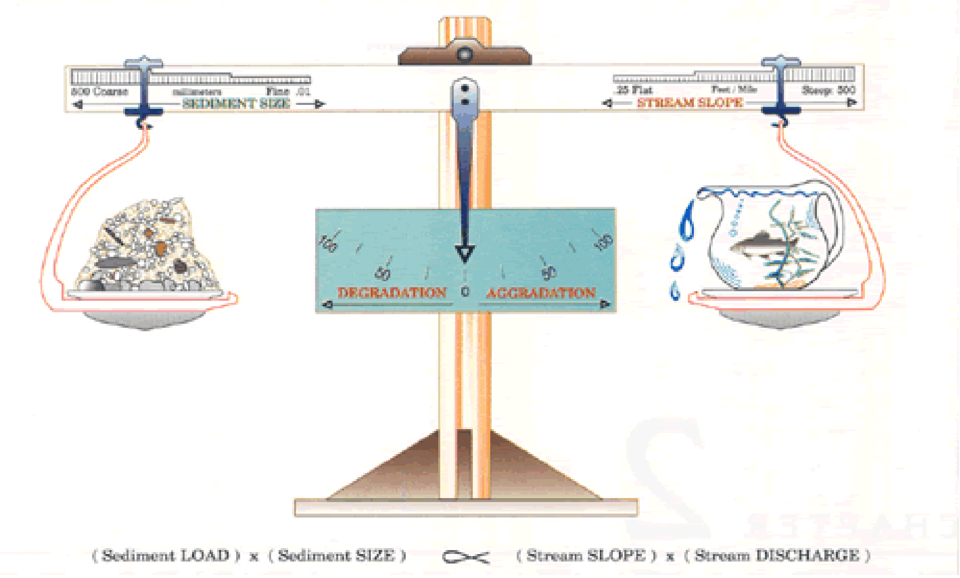

**Figure 14:** Lane's classic diagram illustrates that the size and volume of sediment transported in a stream channel is proportional to the channel slope and the stream discharge.

The size and volume of sediment transported throughout the range of a watershed's flood events, not merely the volume of water transported, is critical to any stream or meadow restoration design. Lane's classic diagram demonstrates that the size and volume of sediment transported is proportional to the flow rate and channel slope (Figure 14). Steeper stream systems are often associated with bedload that is coarser (gravels and even cobbles) than the bedload typically associated with meadow streams. Plugging of the designed, post-project base flow channel with this coarse bedload, initiated by sediment deposition in the channel or a tree falling across the channel, can result in a diversion of the base flow channel much like that accomplished by beaver. Flatter meadow systems may need to transport sediment and that sediment would likely be finer than for steeper systems. However, the volume of sediment transported to the project reach may be large and could result in sediment deposition in the meadow reach, causing a rise in the channel bed elevation that may divert flow out of the designed base flow channel. Some meadow stream systems may not need to be designed to transport sediment. Analysis of the designed channel's ability to transport the predicted size and volume of sediment delivered to the channel is critical to the long-term success of any stream restoration project. Project design also needs to consider that capture of a stream's sediment load within the pond-and-plug reach could affect the sediment / water balance such that erosion processes downstream of the project are accelerated.

Low differences in pond elevations at each plug are clearly desirable. However, such low differences are physically difficult to achieve in meadow systems that are steeper. Figure 15 depicts a simple representation of example pond elevation differences for a flatter and a steeper meadow (the figure is meant only to demonstrate elevation differences; actual constructed plug shapes are more complex). For a 0.5% meadow, plugs can be spaced 100 feet apart and a pond elevation difference of 6 inches will exist. For a 2.0% meadow, plugs that are spaced just 63 feet apart result in a pond elevation difference of over 1 foot. To reduce that difference, plugs would have to be spaced closer together, approaching the point where the gully is nearly filled with plug material, which becomes economically infeasible for larger incisions.

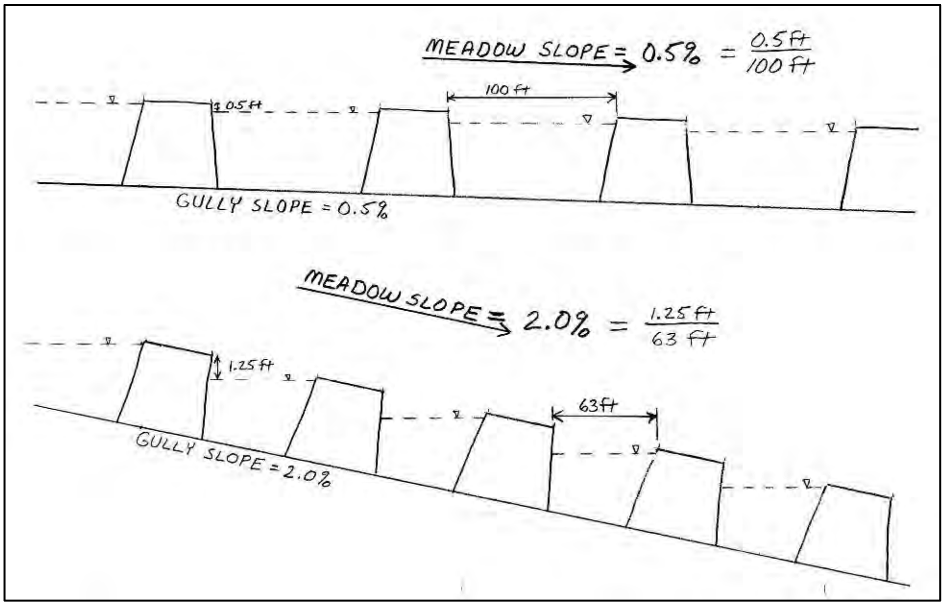

**Figure 15:** Example valley profiles for a flatter and a steeper meadow demonstrate the higher pond elevation differences inherent with steeper meadows.

Pond-and-plug treatments on steeper meadows are much more challenging and require more careful design. Flood modeling needs to be performed to calculate the depth and duration of flow that may run over the plugs. Generally, plugs with a head of 1.0 feet or more should be subjected to very infrequent flood flows of shallow depths so that the plug vegetation can resist the erosive shear stress. Conventional engineering charts for vegetated channels can be used to predict whether the vegetation will withstand the shear stress (USDoT 2005). Installation of imported rock across a plug surface, while expensive, is a potential mitigation for plugs that will be subjected to erosive flood flows. Willow and sedge mat transplants can also be used to armor plug surfaces.

Design consideration should be given to the notion that the modeled floodplain width could be restricted if flood flows occur when deep snow depths exist on the floodplain. Such snow depths could confine the flood flow, resulting in deeper, more erosive flows, both within the low flow channel and on the floodplain (potentially including plug surfaces). While investigating mortality effects of winter floods on fisheries, Erman, et al reported that large flows occurred with snow on the ground during six separate floods between 1953 and 1988 at the UC-Berkeley field station on Sagehen Creek near Truckee, CA (Erman 1988). These researchers surmise that increased shear stress due to snow confining flow to the channel would increase the sediment transport rate by approximately an order of magnitude for the winter flood measured in 1982, when dead Paiute sculpin were collected during bedload sampling. Much of the study reach is located in a forested riparian area and these researchers assert that the effect of snow confining flood flows would be more prevalent in meadow systems. The Sagehen Creek station is located at an elevation of 6300 feet in a basin that averages 37 inches of precipitation per year. The frequency of snow-confining flows, and the depths of snow experienced, would likely be reduced for lower elevation sites and for drier sites.

For steeper reaches approaching 3% - 4%, the difference between pond elevations at plugs can reach 3 – 6 feet. Clearly, flood flow over these plugs should not be considered a stable design unless the plugs are constructed more like grade control structures with hardened surfaces and spillways. Additionally, for plugs that approach this head, engineering design elements for conventional earthen dams should be evaluated or employed to prevent piping through the plug. Such elements may include controlled compaction of suitable, low permeability plug material and / or installation of a plug core consisting of clay or similar material of very low permeability. If a plug looks like a dam and acts like a dam, it should be designed, constructed and monitored as a dam.

Finally, assessment of the hydrologic success of any restoration project, including pond-and-plug projects, should include a definition of what “failure” and “success” mean. Flow that cuts across a plug is not likely a failure if the new path is stable or if the flow can be easily diverted back to a location that is stable in the long-term. A minor amount of repair to a grade control structure as a result of a large flood is not likely a failure if the integrity of the project upstream and the meadow base level were maintained. A project which loses a number of plugs in a flood and is left in an unstable condition that can not be repaired without essentially re-doing the treatment is likely a failure. Consideration should also be given to the consequences of not doing any treatment. Leaving the system to continually degrade, widen, and erode vast amounts of meadow could also be considered a “failure.”

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# Appendix A: List of Pond-and-Plug Projects Implemented in Upper Feather Watershed

| Project Name | HUC-5 Watershed | Date | Private Land | USFS Land |
|---|---|---|---|---|
| Big Flat (Cottonwood Cr) | Last Chance Creek | 1995 | | Plumas |
| Willow Creek | Upper Indian Creek | 1996 | | Plumas |
| Bagley Creek II | Red Clover Creek | 1996 | | Plumas |
| Ward Creek | Lower Indian Creek | 1999 | X | |
| Little Schneider Creek | Spanish Creek | 1999 | | Plumas |
| Clarks Creek | Last Chance Creek | 2001 | | Plumas |
| Stone Dairy | Last Chance Creek | 2001 | | Plumas |
| Carman Creek (Knuthson Mdw) | Sierra Valley | 2001 | | Tahoe |
| Hosselkus Creek | Lower Indian Creek | 2002 | X | Plumas |
| Last Chance Phase I - Pvt | Last Chance Creek | 2002 | X | |
| Carman Creek (3-Corner Mdw) | Sierra Valley | 2002 | | Tahoe |
| Greenhorn Cr (New Eng Ranch) | Spanish Creek | 2002 | X | |
| Last Chance Phase I - USFS | Last Chance Creek | 2003 | | Plumas |
| Poplar Creek | Lake Davis – Long Valley | 2003 | X | Plumas |
| Humbug - Charles | Lake Davis – Long Valley | 2004 | X | |
| Last Chance - Charles | Last Chance Creek | 2004 | X | |
| Ross Meadow | Lake Davis – Long Valley | 2004 | | Plumas |
| Dooley Creek – Downing Mdw | Last Chance Creek | 2005 | X | Plumas |
| Jordan Flat | Last Chance Creek | 2005 | | Plumas |
| Humbug – Charles II | Lake Davis – Long Valley | 2006 | X | |
| Hosselkus Creek II | Lower Indian Creek | 2006 | X | |
| Red Clover – McReynolds Creeks | Red Clover Creek | 2006 | X | Plumas |
| Sulphur Creek KV | Lake Davis – Long Valley | 2007 | | Plumas |
| Rapp – Guidici (Sulphur Cr trib) | Lake Davis – Long Valley | 2007 | X | |
| Dixie Creek | Red Clover Creek | 2007 | X | |
| Last Chance – Ferris Fields | Last Chance Creek | 2007 | | Plumas |
| Smith Creek | Lake Davis – Long Valley | 2008 | X | |
| Boulder Creek (Sulphur Cr trib) | Lake Davis – Long Valley | 2008 | X | |
| Long Valley Creek | Lake Davis – Long Valley | 2008 | X | |

### Science to Solutions

# Private Lands Vital to Conserving Wet Areas

## for Sage Grouse Summer Habitat

***In Brief:*** In the arid West, life follows water. Habitats near water – streamsides, wet meadows and wetlands — support the greatest variety of animal and plant life, and attract wildlife during their daily and seasonal movements. In a water-scarce landscape, these lush habitats are also where people have naturally settled. A recent groundbreaking study reveals a strong link between wet sites, which are essential summer habitat for sage grouse to raise their broods, and the distribution of sage grouse breeding areas or leks. The authors found 85% of leks were clustered within 6 miles of these wet summer habitats. Moreover, although wet habitats cover less than 2% of the western landscape, more than 80% are located on private lands. This study makes it clear that successful sage grouse conservation will greatly depend on cooperative ventures with private landowners, ranchers and farmers to help sustain vital summer habitats.

## Green Magnets for Grouse

The sage grouse's life history is intimately linked to sagebrush shrubsteppe uplands. Yet in late summer, as the uplands dry out, hens seek out emerald islands in the sagebrush sea: riparian edges, wet meadows, seasonal wetlands, and irrigated fields — remaining spots of green where they can still find moist forbs and plenty of insects for their growing chicks. These scattered wet habitat sites are critical for brood survival and recruitment.

*Do these islands of late summer green somehow influence where sage grouse choose to breed in spring? And how does summer habitat fit into the conservation picture for sage grouse?*

To answer these questions, Patrick Donnelly with the Intermountain West Joint Venture/U.S. Fish and Wildlife Service (IWJV/USFWS) and his co-authors Dave Naugle and Jeremy Maestas with the Sage Grouse Initiative (SGI), and Christian Hagen with Oregon State University (OSU), mapped sage grouse breeding sites in relation to wet habitats across a large landscape, and analyzed the land ownership of wet habitat sites.

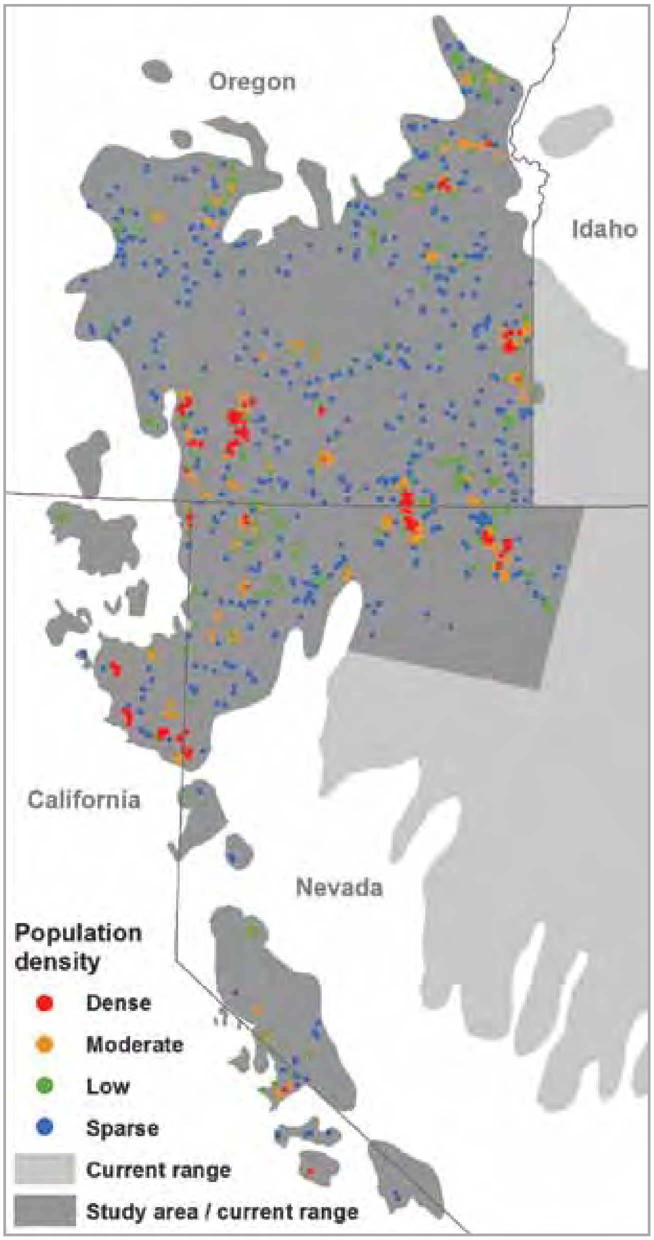
*In late summer, wet meadows, riparian edges, and irrigated fields become islands of green in the sagebrush sea – vital foraging habitat for growing sage grouse broods. Photo credits: top - Dan Taylor; bottom left - Conservation Media; bottom right - Ken Miracle.*

# Lek Counts and Landsat

The authors studied patterns in the distribution of sage grouse breeding sites (leks) and summer habitats over a 28-year period (1984-2011) by taking advantage of two existing long-term datasets: annual lek survey data collected by the states and Landsat satellite imagery. The study area covered more than 32 million acres of current sage grouse range, encompassing populations in California, Oregon and northwestern Nevada. The scientists examined location and count data for 1,277 active lek sites in relation to habitat cover interpreted from Landsat satellite imagery. Using lek survey data they could categorize breeding areas by sparse, moderate or dense populations.

Landsat images used to map wet habitats were acquired for each year in late summer (August and September) during a time when sage grouse rely heavily on these resources for food. This allowed the authors to account for annual variations in climate and determine how changes altered summer habitat distribution during wet and dry periods. Summer habitats were classified as natural or agricultural areas. Natural sites included riparian areas, seasonal and temporary wetlands, as well as reservoirs, lakes, and playas with moist vegetation. Agricultural sites included wet meadows and alfalfa fields. Although wet meadows form naturally in basins, more than 92% of wet meadows in the study area were irrigated.

Once mapping was complete, the team could examine the spatial relationship between summer habitat locations, the likelihood of a habitat site being wet from year to year, and the distribution and abundance of sage grouse based on lek surveys. In addition, the researchers overlaid land ownership maps with wet habitat locations to establish whether late summer sage grouse habitat is more likely to be on pubic or private land.



*The study area encompassed sage grouse range in Oregon, California and northwest Nevada. Colored dots represent leks. Grouse leks and populations cluster in the landscape: red and yellow indicate higher breeding densities; blue and green are more sparse. Map courtesy of Patrick Donnelly, IWJV/USFWS.*

In late summer, sage grouse seek out productive wet habitats in both natural and agricultural areas. In this study, natural sites included riparian habitats, seasonal and temporal wetlands, and the edges of reservoirs, lakes, and playas with moist vegetation. Agricultural sites included alfalfa fields and wet meadows, which were most often associated with irrigation.

# Summer Habitats Connect Sage Grouse with Private Lands

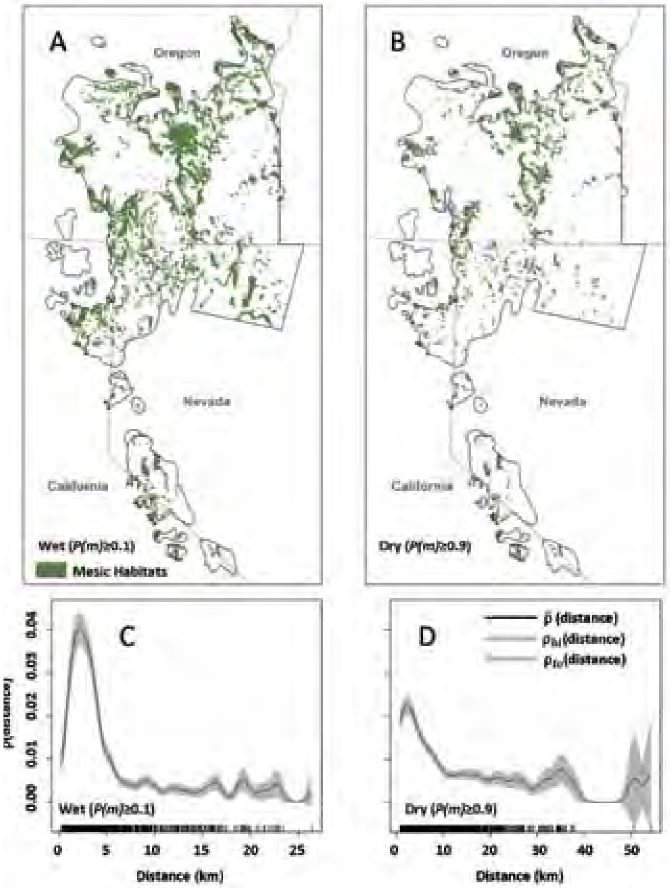
Several patterns quickly became clear. Not only were leks clumped in the landscape, but the distribution of those clusters were strongly linked to the location of wet habitats: 85% of leks were within 6.2 miles of wet sites. The breeding areas with the highest densities of birds were even closer – within only 1.8 miles of wet habitats. In other words, the scarcity of wet habitats in sagebrush ecosystems drive the location of grouse breeding sites on uplands: hens choose to mate and nest within a reasonable walk of where they can find late summer foraging for their broods.

While sagebrush uplands are characteristically more stable environments, the study found the extent of wet summer habitats varied greatly from year to year with shifting climate patterns. In dry years, grouse broods must walk farther to find adequate summer foraging sites – the distance can double, increasing nutritional stress and making hens and chicks more vulnerable to predation.

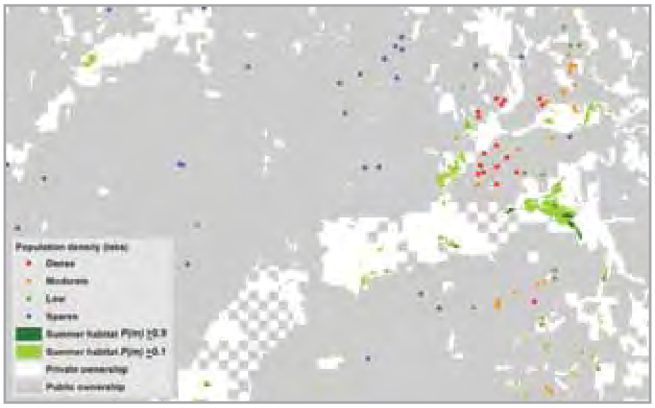
Grouse breeding sites with larger populations were also linked to the best natural summer habitats, and in wet years these sites may drive population recruitment: more chicks survive. On the other hand, sparsely populated breeding areas were farther from summer habitats and often associated with irrigated agriculture. During drought, grouse find fewer options for late summer foraging and may rely more on irrigated fields and wet meadows, when natural sites dry out.

European settlers to the Great Basin well understood the best sites for farms and pastures, and settled stream bottoms and basins that collect snowmelt and remain productive late into summer. Donnelly and his team overlaid current land ownership with 1887 maps of topographic basins and with Landsat imagery of current wet habitat condition. The natural basins that support both temporary and persistent wet habitats were magnets for settlers, and virtually all are in private ownership today. The authors found that while wet habitats make up only 1 to 2% of the land area, 81% are in private hands.

> *"I don't think it was so much a surprise that grouse rely on these wet areas and that wet habitats are limited; it was how much of this was private, and how much wet summer habitat controlled the distribution of grouse across the landscape."*
> ~Patrick Donnelly, IWJV/USFWS



*In wet years, the extent of wet (mesic) habitats can nearly double (maps at top). Hence leks are much closer to summer habitat (bottom graphs) – an easier trek from nesting areas for hens with broods. Chart courtesy of Patrick Donnelly, IWJV/USFWS.*



*Mapping leks, wet summer habitats and land ownership revealed a startling pattern: although >80% of upland breeding habitat is on public lands, >80% of critical summer brood habitat is located on private lands. Chart courtesy of Patrick Donnelly, IWJV/USFWS.*

## An Essential Piece of the Conservation Puzzle

Conventionally, sage grouse conservation has focused on management of sagebrush uplands, yet this study reveals that wet summer habitats and private land partnerships are vital for sustaining sage grouse. "How do you conserve grouse that split their time between private and public lands?" asks Donnelly. "With 81% of sparse summer habitat in private ownership, sage grouse success is inextricably linked to ranching and farming in the West."

Conservation must consider the connection between seasonal habitats on public and private lands and involve cooperative efforts with private landowners. By understanding the importance of privately-owned summer habitats to sage grouse, conservation pracitioners can use existing volunteer and incentive-based programs to target conservation easements, and focus investment in cooperative programs to reduce threats to, restore, and enhance these habitats.

## How Can I Access this Data?

IWJV and SGI have created a map-based "Decision Support Tool" for land managers to help identify summer grouse habitat and coordinate conservation. The tool can be used to target summer habitat areas for conservation, and to evaluate the outcomes of conservation efforts. The tool is available on the SGI website as an ArcGIS data package and must be downloaded to an ArcGIS platform. If you are a private landowner interested in using this decision tool, or have no ArcGIS capability, contact your NRCS field office for assistance.

The tool can help practitioners:

- Target protection, enhancement and restoration of summer habitats in priority landscapes.
- Maintain or expand available summer habitat to sustain grouse distribution and abundance.
- Coordinate conservation efforts across public and private lands.

Currently, the decision tool only covers sage grouse range in Oregon, California and northwest Nevada. Work is underway to expand the study and provide a tool for the entire sage grouse range across 145 million acres within the next two years.

To view the science webinar, "Rangewide Mapping of Scarce Wetland Resources", presented by Patrick Donnelly, visit http://www.sagegrouseinitiative.com/private-lands-harbor-scarce-wetlands-ideal-sage-grouse-view-science-webinar/

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*Patrick Donnelly with the IWJV/USFWS in Missoula, Montana, lead this ground-breaking study that revealed a tight link between sage grouse upland breeding sites and nearby wet summer habitats. Photo courtesy of Patrick Donnelly.*

## Suggested Citation

Sage Grouse Initiative. 2014. Private Lands Vital to Conserving Wet Areas for Sage Grouse Summer Habitat. Science to Solutions Series Number 4. Sage Grouse Initiative. 4pp. **http://www.sagegrouseinitiative.com/.**

## Source

Donnelly, J.P., D.E. Naugle, C.A. Hagen and J.D. Maestas. In preparation. Public lands and private waters: scarce summer habitat and land tenure structure sage-grouse distributions.

## Additional Resources

To learn more about sage grouse conservation and the Sage Grouse Initiative, visit the SGI website at **http://www.sagegrouseinitiative.com/.**

To find your local NRCS Service Center, visit the NRCS website at **http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/contact/local/.**

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*September 2014.*

# Red Clover/McReynolds Creek Restoration Project Monitoring Report 2010

Ryan Nupen fly fishing in project area June 2010. (Photo G. Martynn)

## Feather River Coordinated Resource Management
## Plumas Corporation
## Spring 2011

## Background

This Annual Monitoring Report, for the Red Clover/McReynolds Creek Restoration Project, covers monitoring and results from 2010 for a few select metrics. This report tiers to the 2007 – 2009 Monitoring Reports. Past monitoring reports, which display data from all metrics, are available at the Plumas Corporation office and at www.feather-river-crm.org on the Red Clover McReynolds project page.

Due to a lack of on-going funding for project monitoring, the Feather River Coordinated Resource Management group (FRCRM) was only able to continue monitoring water temperature, stream flow, turbidity, and fish for this project in the 2010 water year. In 2010 avian monitoring was conducted by PRBO Conservation Science, Plumas National Forest, and Plumas Audubon and is included in this report. Monitoring from on-going watershed monitoring efforts by the FRCRM, helped to answer some of the monitoring questions as discussed below.

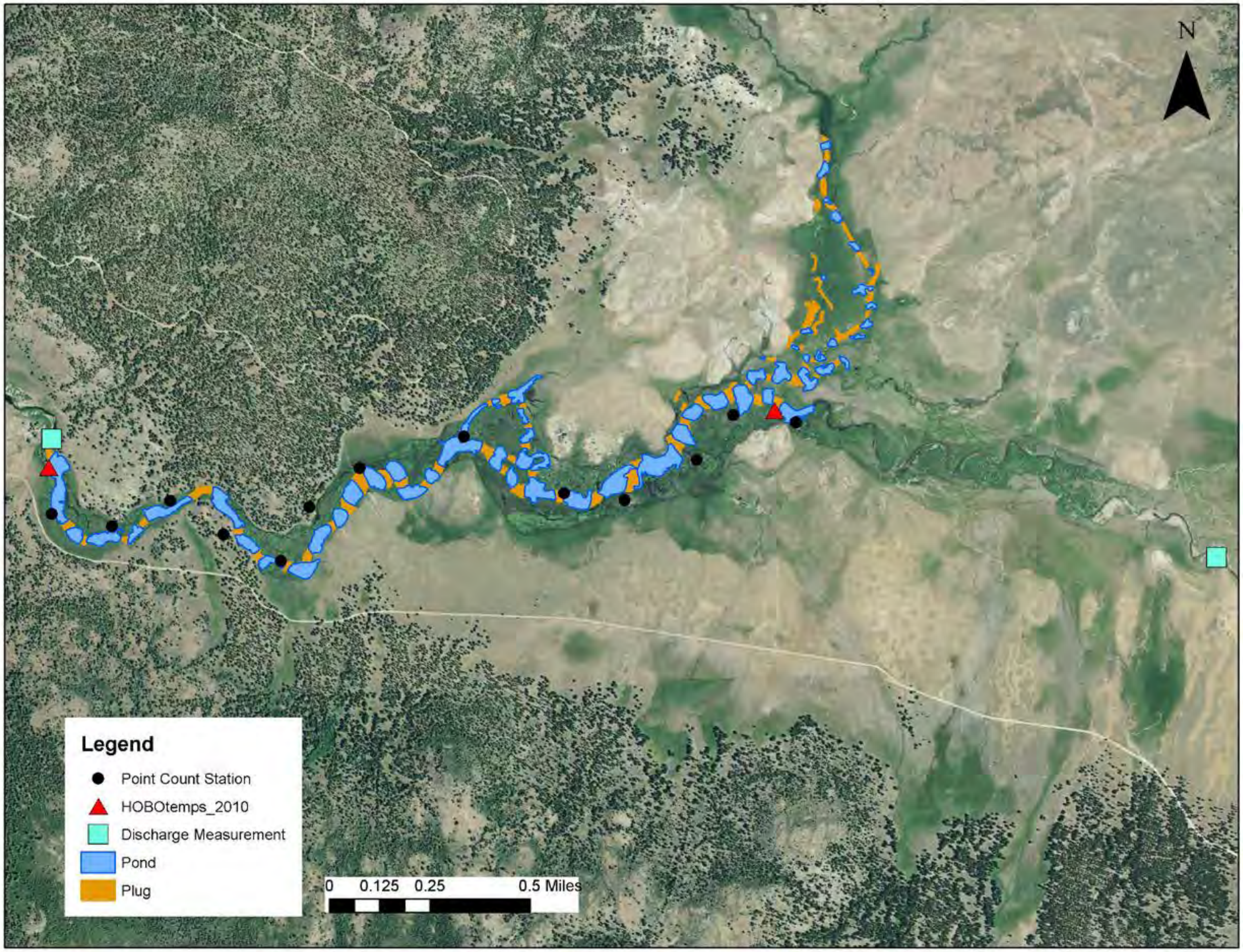
The purpose of this document is to report the results of a fourth year of project effectiveness monitoring, as implemented according to the Project Monitoring Plan. The project was constructed in 2006, from July through November. Most pre-project monitoring was completed in 2005. Post-project monitoring reported herein was conducted in 2007-2010.

The Red Clover McReynolds project area is just downstream of, and partially within, a check dam project implemented by the FRCRM in 1985. Results of the 1985 monitoring effort can be found at www.feather-river-crm.org.

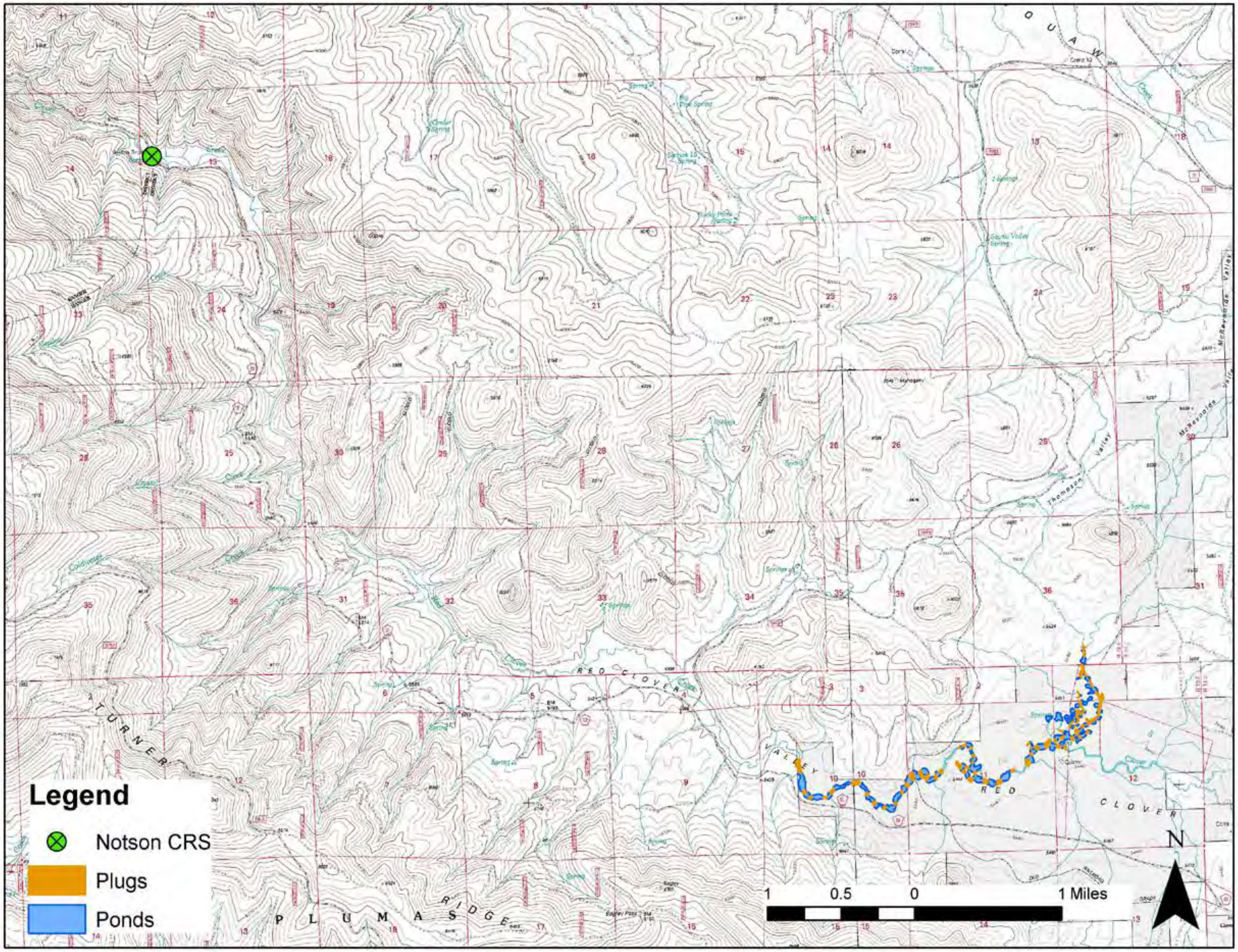
## Project Overview

In 2006, 3.3 miles of gullied stream channel immediately downstream of the 1985 project was eliminated. Stream flows were returned to remnant channels at original meadow/channel elevations utilizing the "pond and plug" technique, restoring the functionality of 400 acres of floodplain within Red Clover Valley, along Red Clover and McReynolds Creeks on both private and public lands. Pond and plug is a technique that obliterates a gullied channel by replacing it with a series of earthen plugs and ponds. The excavation of the ponds provided the fill material for the plugs. The Red Clover/McReynolds Creek Restoration Project consists of 59 ponds and 66 plugs. The primary project goal was to improve the water and sediment retention functions of the watershed, with objectives focusing on reduced bank erosion, improved water quality, improved fish and wildlife habitat, reduced flood flows, and increased base flows. Primary funding ($1,101,000) was provided through the State Water Resources Control Board Proposition 13 CALFED Watershed Program, with contributions from Department of Water Resources, Natural Resources Conservation Service, U.S. Forest Service-Plumas National Forest, the landowner, and volunteers.

## Map 1: Monitoring Locations in the Red Clover/McReynolds Creek Restoration Project



**Map 2: Notson Bridge in relation to Red Clover/McReynolds Creek Project Area**



## Base Flow

Stream discharge measurements, to analyze the project's effect on base flow, are taken at two spatial scales. The watershed scale is measured at Notson Bridge, located nine miles downstream of the project area at the FR-CRM's continuous recording station, which has been operating since 1999. This station collects stream stage, air temperature, and water temperature every 15 minutes with a Campbell CR10X data logger. The stage and temperature readings are stored as hourly averages and then summarized into daily files at the end of each water year. The FR-CRM staff are responsible for capturing discharge measurements over the range of flows to maintain/update a rating table. The rating table is reviewed and updated annually by Sagraves Environmental Services.

Project scale base flows are also measured 1.5 miles above the McReynolds Creek confluence and below the project grade control structure. Flows at the Notson Bridge station also include several tributary channels, and project effects on flow may be diluted by the time flows reach this station.

Results:

Figure 1 displays pre- and post-project base flows at Notson Bridge in 2000 and 2010. 2000 and 2010 were compared because of the similarity in amount of precipitation (101% of normal precipitation) between these water years. The baseflow discharge in both years is very similar, though 2000 was the end of a wet decade and 2010 was the end of a dry decade. Data are missing from July 5 to August 10, 2000 due to problems with the equipment. The normal historic average precipitation is from the California Department of Water Resources' (DWR) California Data Exchange Center website (http://cdec.water.ca.gov/).

**Figure 1. Pre-project vs. Post-project hydrograph at Notson Bridge.**

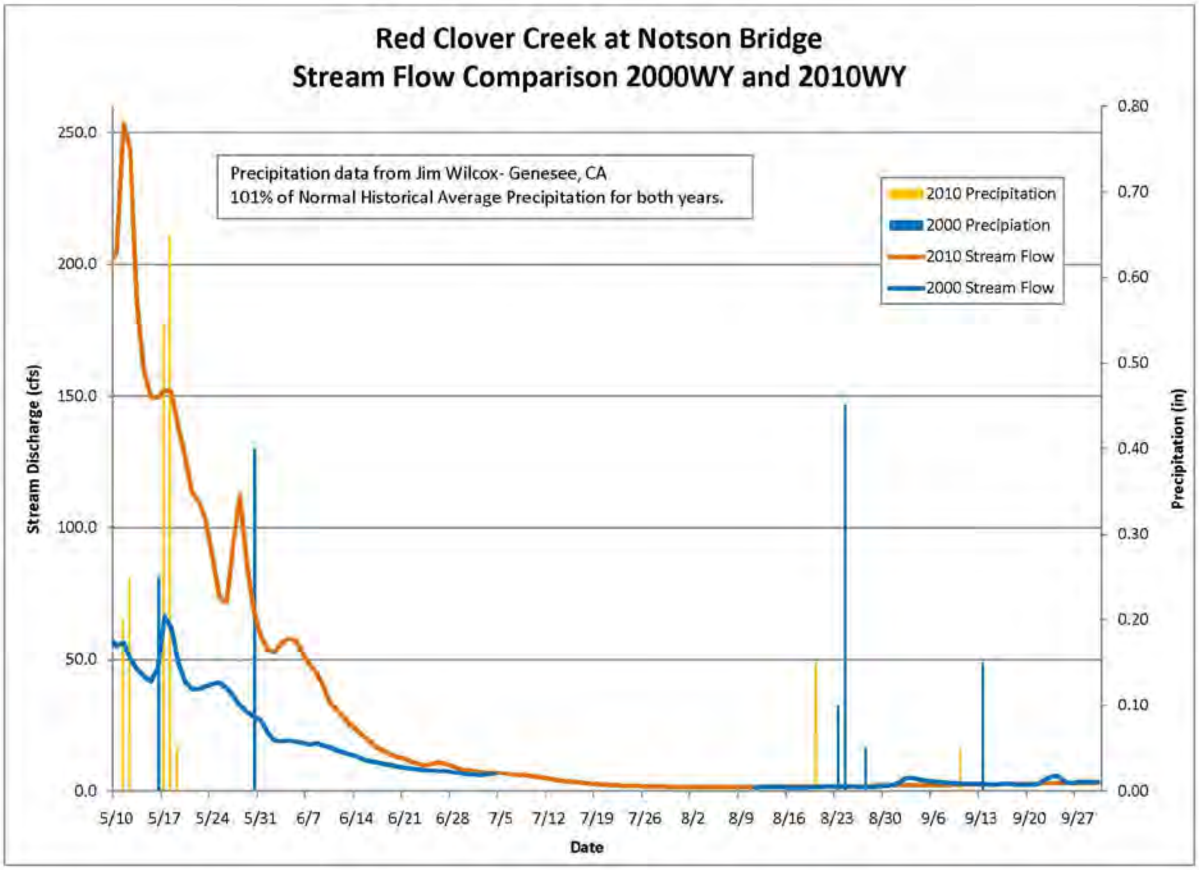


Table 1 shows precipitation totals at Doyle Crossing and Genesee Valley for water years 2001, 2002, 2006-2010 to provide context for Figure 1 and Table 2.

**Table 1. Precipitation totals at Doyle Crossing and Genesee Valley**

| **Water Year** (10/1-9/30) | 2000 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 |
|---|---|---|---|---|---|---|---|
| **Doyle X-ing Precip (in)** | Not available | 14.56 | 29.47 | 11.07 | 11.49 | 17.11 | 14.55 |
| **Genesee Precip (in)** | 43.3 | 45.50 | 66.25 | 31.05 | 25.40 | 38.05 | 33.85 |

Monthly flow measurements from June through September are taken at the top of the project above McReynolds Creek, and at the bottom of the project just below the rock grade control structure. Flows are measured with a Marsh-McBirney FLO-MATE following the USGS stream discharge measurement protocol. Table 2 on page 6 shows the results of these measurements.

Discussion:
The expectation is that the 2010 data in Figure 1 would show an increase in base flow compared to 2000 due to the project, despite the fact that 2000 was the end of a wet decade and 2010 was the end of a dry decade. However, starting in July the base flows from both years are almost identical. There are small increases in base flow as the season progresses in 2000, due to precipitation events.

In Table 2 (pg 6) the rapid decline in flows from June to July (>90% decrease) seen in pre-project conditions indicates the poor condition of the watershed, and the lack of seasonal storage and release in the project area. It is also interesting to note that there is less water at the bottom of the project area than at the top for every measurement pre- and post-project, except June 2005. The loss may be due to evapotranspiration, or it may be lost into a deep aquifer. The increase of flow in September suggests that the loss is due, at least in part, to evapotranspiration.

The major decline in flows between pre- and post-project conditions was most likely due to three years of drought after project completion. However, in 2007 through 2009, despite the lack of precipitation, there was a less dramatic decline in flows from June to July. The 2010 water year had 20-40% more precipitation than the past few water years and surface water flowed through the project area all year.

It should also be noted that there is a significant difference between the flows at the top of the project between 2007 and 2008-2010. The flow at the top of the project drops to zero during August and September of 2007, while during the same months of 2008-2010 the flows are about 1.5 cfs. It is unclear why inflow dropped to zero in 2007. The measurement cross-section at the top of the project was moved in 2008 to above the 1985 check dam project. Measurement location was moved due to changes in flow at the top of the project area caused by beaver.

**Table 2. Pre- and Post- project monthly flow measurements at top of project (above (abv) McReynolds Cr) and below (blw) project area (in cubic feet per second).**

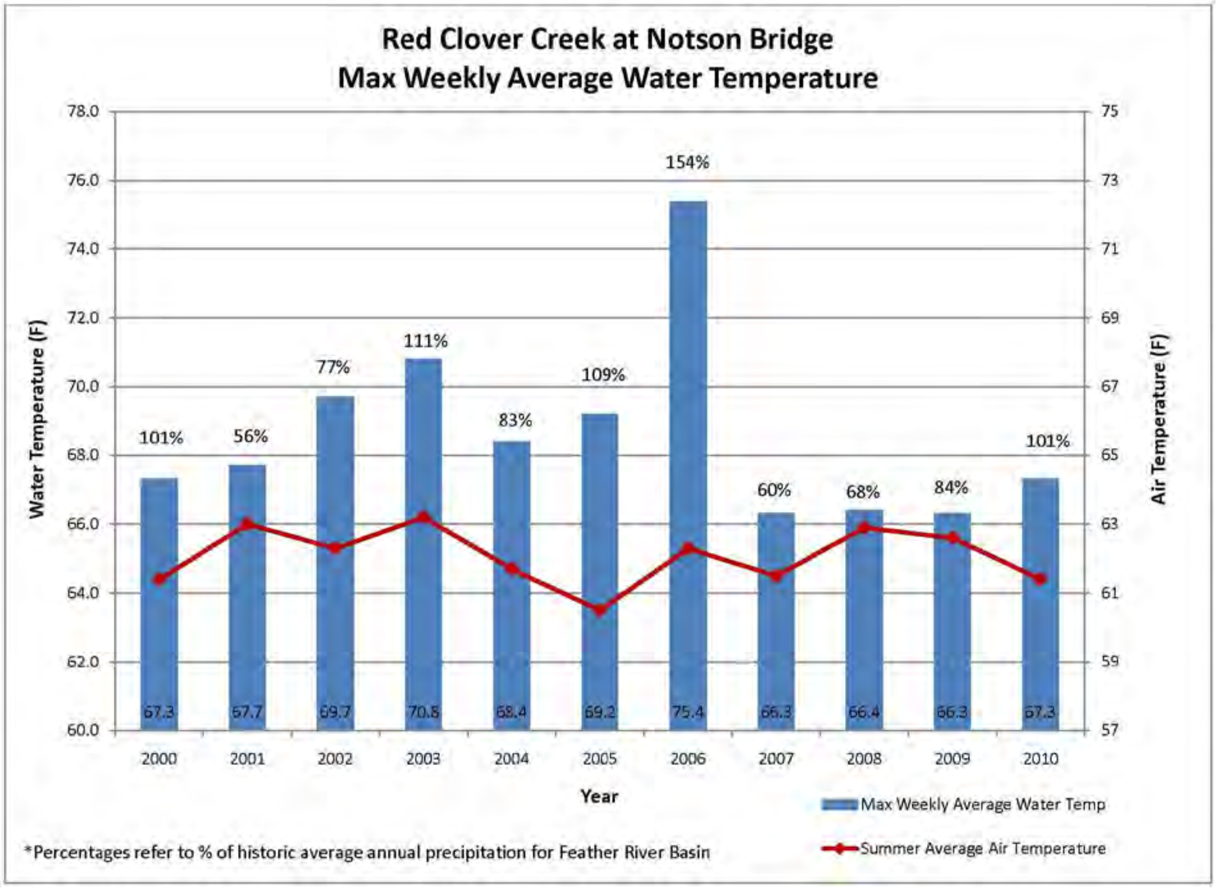
| Month | June | | | | | July | | | | | August | | | | | September | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | pre 2005 | post 2007 | post 2008 | post 2009 | post 2010 | pre 2005 | post 2007 | post 2008 | post 2009 | post 2010 | pre 2005 | post 2007 | post 2008 | post 2009 | post 2010 | pre 2005 | post 2007 | post 2008 | post 2009 | post 2010 |
| Abv McReynolds | 15.3 | 3.8 | 2.36 | 6.88 | 16.46 | 1.4 | 1.2 | 2.14 | 1.62 | 3.2 | 1.4 | 0 | 1.37 | 1.49 | 1.88 | 1.8 | 0 | 1.51 | 1.39 | 1.6 |
| Blw project | 17.8 | 2.6 | 1.64 | 6 | 16.14 | 1 | 0.1 | 0.49 | 0.61 | 1.36 | 1.1 | 0 | 0.002 | 0.01 | 0.04 | 1.6 | 0 | 0 | 0 | 0.6 |

## Water Temperature

All stream and pond water temperatures are recorded using a HOBO Temp® water temperature logger. Water temperature at the bottom of the project area is only available through July 2010, due to loss of the temperature logger at the bottom of the project area once the Red Clover Poco project construction commenced. The HOBO will be picked up hopefully summer 2011. Until then late summer water temperature data are not available.

Figure 2 shows the maximum weekly average water temperature at Notson Bridge, compared with summer average air temperature and historic average annual precipitation for the Feather River Basin. Summer average air temperature is an average of DWR weather stations at Antelope Lake, Doyle Crossing, Quincy, and Grizzly Ridge from June 1 through September 30. This graph shows that even though 2007 through 2010 were some of the lowest water years in the past 10 years of monitoring at Notson Bridge, they had the lowest maximum weekly average water temperatures. A comparison between 2000 and 2010, both with 101% normal annual precipitation and 61.4 °F summer average air temperature, shows that both years have the same maximum weekly average water temperature (67.3°F).

**Figure 2. Maximum (max) Weekly Average Water Temperature at Notson Bridge.**

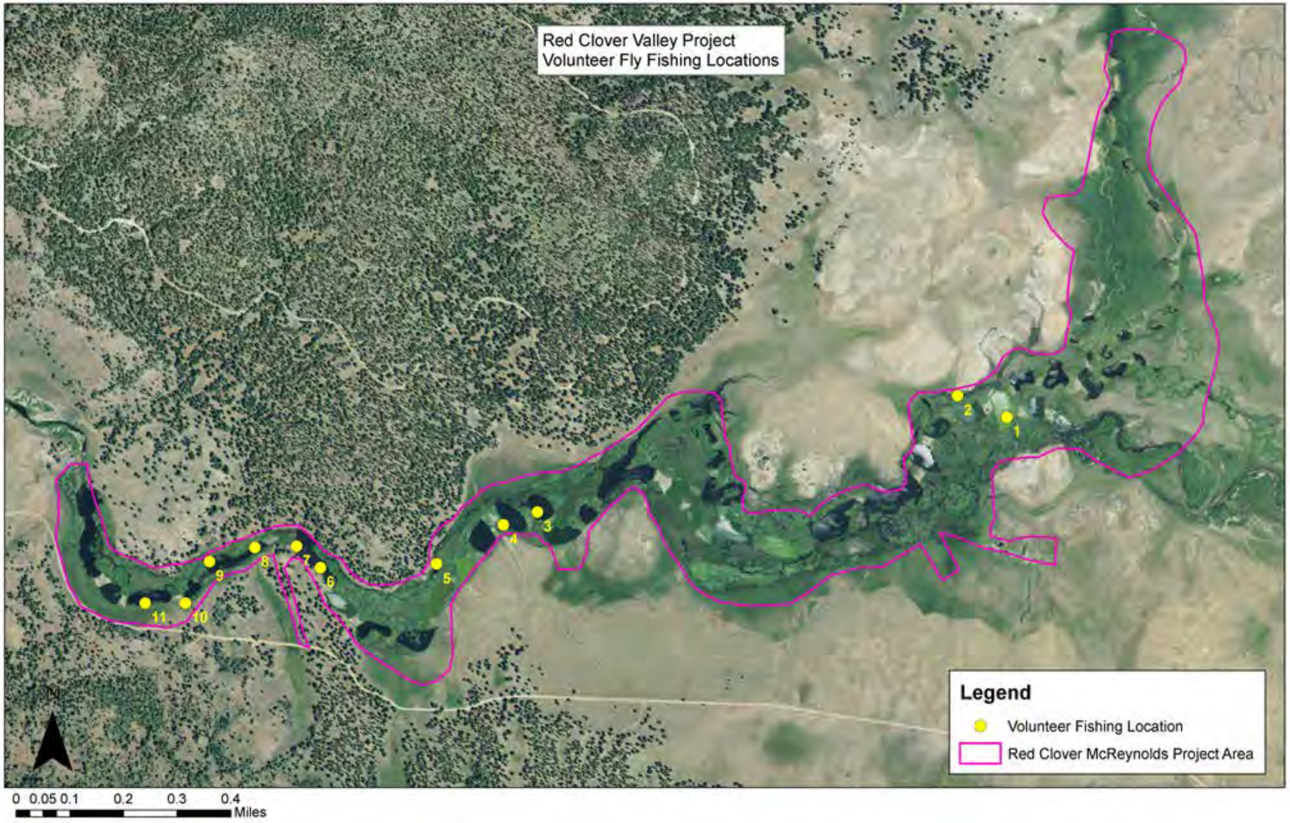


*Percentages refer to % of historic average annual precipitation for Feather River Basin

## Fisheries

To remediate difficulties with sampling technique in the past, the FRCRM has made use of volunteer fishing days. There have been two volunteer days since project construction, one in June 2008 and one in June 2010. See Table 3 and Map 3 for data from volunteer fishing efforts. Pre-project electroshocking found very few trout. Only one trout (3.5 inches long) was found out of the three sampling areas (please reference past monitoring reports for complete electroshocking data). Despite the lack of comparable pre- and post- project sampling techniques, it appears that the fishery continues to improve in the project area.

### Map 3. Red Clover McReynolds Volunteer Fishing Locations



### Table 3. Red Clover Creek post-project volunteer fishing days.

| June 2008 | | | | June 2010 | | | |
|---|---|---|---|---|---|---|---|
| Location** | Species (Trout) | Size (In) | Visual Only | Location** | Species (Trout) | Size (In) | Visual Only |
| 1 | Rainbow | 13 | ✓ | 3 | Rainbow | 12 | ✓ |
| 1 | Rainbow | 15 | | 4 | Rainbow | 15 | |
| 1 | Rainbow | 16 | | | | | |
| 2 | Rainbow | 12 | ✓ | 4 | Rainbow | 12 | |
| 6 | Rainbow | 13 | ✓ | 5 | Rainbow | 16 | |
| 6 | Brown | 16 | | 7 | Rainbow | 5 | ✓ |
| 6 | Rainbow | 13 | | 8 | Rainbow | 8 | |
| | | | | 8 | Rainbow | 11 | |
| | | | | 8 | Rainbow | 12 | |
| | | | | 9 | Rainbow | 12 | |
| | | | | 10 | Rainbow | 16 | |
| | | | | 10 | Rainbow | 13 | |
| | | | | 10 | Rainbow | 13 | |
| | | | | 11 | Rainbow | 12 | |
| | | | | 11 | Rainbow | 14 | ✓ |
| | | | | 11 | Rainbow | 12 | |
| | | | | 11 | Rainbow | 18 | |

**Fishing locations are number 1-11 starting at the top of the project

**Photo 1. Volunteer Fishing Day. Craig Martynn and Trout- photo by G. Martynn, 2008**

What is the project's effects on wildlife?

In 2010, avian point count monitoring was initiated by PRBO Conservation Science, Plumas National Forest, and Plumas Audubon. Results were analyzed by comparing all points in unrestored sections of Red Clover Valley (pre-project Red Clover Poco and unrestored Red Clover Confluence and Red Clover Dotta project areas) to post-project Red Clover McReynolds and 1985 Red Clover Demonstration project areas. Figure 3 compares indices of species richness, total bird abundance, and the richness and abundance of riparian focal species. The riparian focal species included in this analysis are Red-breasted Sapsucker, Willow Flycatcher, Warbling Vireo, Swainson's Thrush, Black-headed Grosbeak, Yellow Warbler, MacGillivray's Warbler, Wilson's Warbler, Song Sparrow, and Lincoln's Sparrow. Species richness is the total number of species detected at the point that are adequately sampled using the point count method Total bird abundance is the sum of total individuals detected per visit.

Figure 3 shows that the Red Clover/McReynolds project area is significantly higher than the unrestored sites for all of the metrics. The 1985 Red Clover Demonstration project shows increase in all the metric from the unrestored sites, but due to the small sample size these differences are not statistically significant. This point count analysis was restricted to a subset of the species encountered. Species that do not breed in the study area, as well as those species that are not adequately sampled using the point count method (e.g. waterfowl, raptors, and wading birds), were not included in the analysis.

In 2007-2009 CA Dept. of Water Resources conducted avian monitoring in the Red Clover McReynolds project area using line transect surveys. Data from these efforts are available in the 2007-2009 monitoring reports. Both methods of survey show increased riparian focal species, however point counts do not take into account waterbirds.

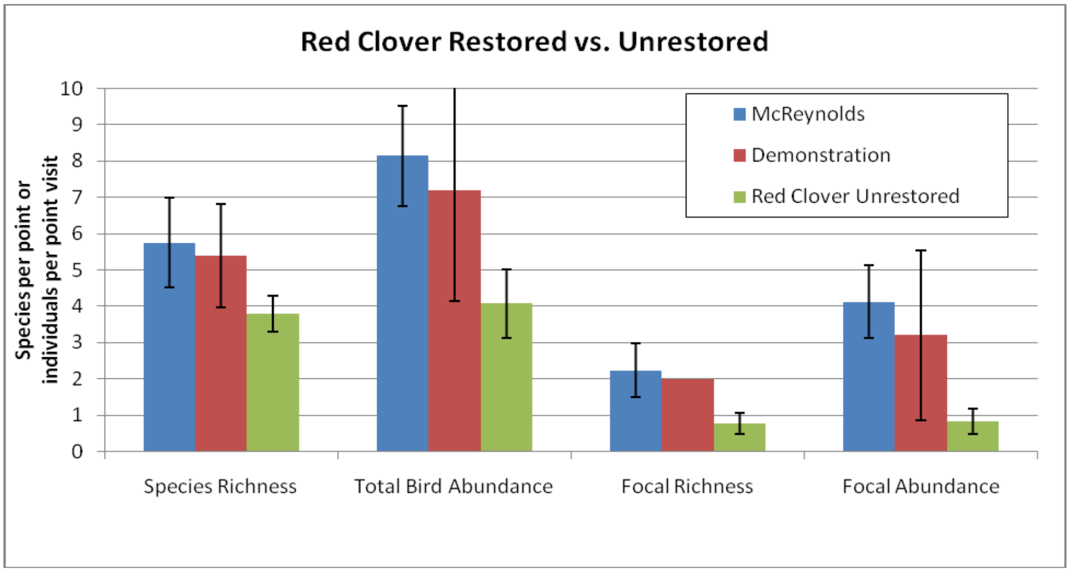


**Figure 3. Red Clover McReynolds Point Count Summary: Point Richness and Abundance**

**Photo 2 and 3. Photo point monitoring of Red Clover Creek at cross-section 19 pre-project June 2006 and post-project June 2008.**

## Erosion/Sedimentation

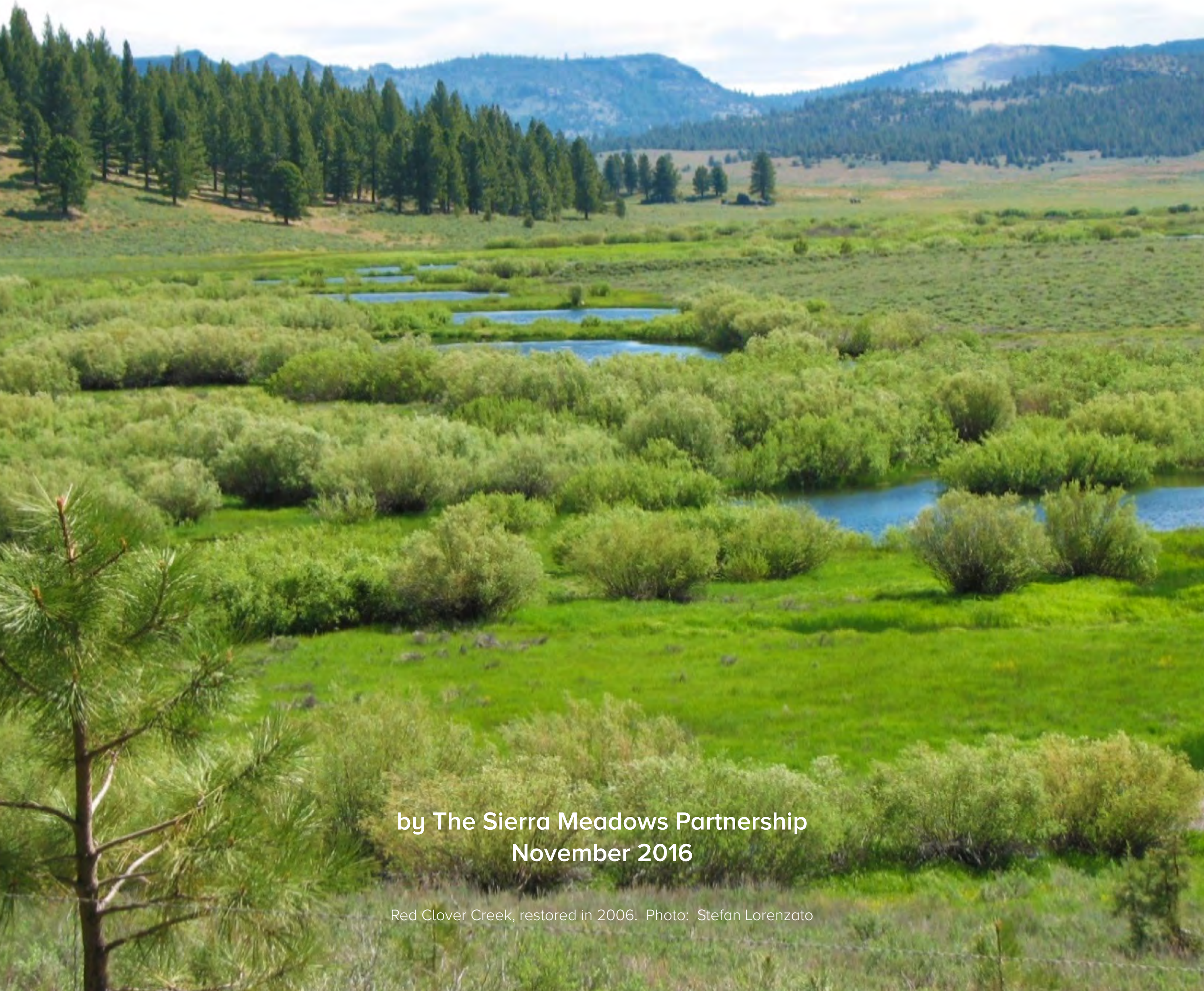
The Red Clover/McReynolds Creek Restoration project has re-established the depositional function in the project area with net erosion expected to be near zero. Restoring this function affects erosion rates in two ways: 1) the source of sediment from gully walls is eliminated; 2) spreading high flows over the vegetated floodplain filters sediment delivered from upstream sources. This was demonstrated through turbidity samples taken during high water events in 2007 through 2010. Turbidity is an indicator of sediment transport levels; it does not take into account settleable solids or bedload. Turbidity is measured using an HF Scientific, Inc. DRT-15CE Turbidimeter.

Turbidity samples were taken at the top of the project area above the confluence with McReynolds Creek and just below the bottom of the project area. Samples are taken during most accessible storm events. Throughout 2007 to 2010, turbidity levels were higher entering the project than exiting the project during high flow events. The outflow turbidity is 50% less than the inflow turbidity for 15 sampling periods during the runoff seasons from 2007-2010 for the Red Clover McReynolds project area. Turbidity samples were collected during one accessible storm event in 2010 and show an 8% decrease in turbidity through the project area.

FULL REPORT

# Sierra Meadows Strategy

An “all-hands, all-lands” approach to
increasing the pace, scale and efficacy of meadow restoration
and protection throughout the Greater Sierra Nevada.



by The Sierra Meadows Partnership
November 2016

Red Clover Creek, restored in 2006.  Photo:  Stefan Lorenzato

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**Suggested Citation:**

Drew, W. M., Hemphill, N., Keszey, L., Merrill, A.,
Hunt, L., Fair, J., Yarnell, S., Drexler, J., Henery, R.,
Wilcox, J., Burnett, R., Podolak, K., Kelley R.,
Loffland, H., Westmoreland, R., Pope, K.
2016. Sierra Meadows Strategy.
Sierra Meadows Partnership Paper 1: PP 40

The Sierra
Meadows
Partnership

Collaborative meadow
restoration and protection.

# Contents

# Section I

## Executive Summary

The Sierra Nevada Region is of great significance to the State of California because it occupies about 25% of California's total land area and is the source area for more than 60% of its developed water supply[1]. In addition, the region contains a rich diversity of ecosystems, supporting 50% of California's plant species and 60% of California's animal species[2,3].

Within the region, the Sierra Nevada's meadows are hotspots in terms of the importance of biodiversity[4,5,6]. Their ecosystems play a vital role in supporting wildlife and plant diversity, providing habitat for all life history stages of many fish and amphibian species, attenuating floods, storing, filtering, and releasing water, sequestering carbon, providing forage for livestock, and providing unique aesthetic and recreational value[7-14]. Healthy meadows add resiliency to the hydrologic and ecological processes that sustain California's headwaters.

## The Importance of Meadows

Current estimates indicate that meadows cover approximately 191,000 acres within the Sierra Nevada. Although this area makes up a relatively small fraction of the greater Sierra Nevada region, meadows' unique hydrologic and ecological functions are recognized as being vital to watershed health and are valued for the ecosystem goods and services they provide[15].

However, approximately 50%, or roughly 90,000 acres of these meadows are known or expected to be degraded, resulting in the loss of important goods and services[16]. Stresses such as climate change and development continue to threaten ecologically important meadows. Given the iconic nature of Sierra meadows and the critical importance of the Sierra Nevada to California water supply, many state and federal agencies have agreed on the urgent need to increase the pace, scale and efficacy of meadow restoration and protection. The Sierra Meadows Partnership was formed, in part, to address this critical need.

## The Sierra Meadows Partnership

The Sierra Meadows Partnership (Partnership) was formed to foster expansion of and more effective collaboration among partners currently engaged in meadow conservation to increase the pace, scale and efficacy of meadow restoration and protection in the Sierra for the benefit of people and ecosystems.

**The shared vision of the Sierra Meadows Partnership is a greater Sierra Nevada region with healthy and resilient meadows that provide sustained goods and services to benefit flora, fauna and people.**

The composition of the Partnership thus far has included stakeholders from non-profit and for-profit natural resource organizations, public natural resource agencies, academia, and funding institutions. The Partnership remains open to new parties, including implementing groups, private land owners, industry, funding interests, and individuals interested in improving the ecological health of mountain meadows.

At Calistoga Meadows Workshop II, members of the Partnership collaborate to develop structure and content of the Strategy. Photo: M. Drew

A solid foundation of partnerships among private, state and federal land managers, advocacy groups, restoration practitioners, land trusts, and research institutions exists, and these partnerships have been critical to realizing the restoration of approximately 10,000 acres of montane meadow to date[17].

## The Sierra Meadows Strategy

This Sierra Meadows Strategy (Strategy) aligns with the:

- State Water Action Plan which calls for 10,000 acres of meadows to be restored[18];
- Sierra Nevada Conservancy's Watershed Improvement Program Regional Strategy that supports meadow restoration since meadow health is critical to stream condition and downstream water quality[19];
- National Fish and Wildlife Foundation Sierra Meadows Restoration Business Plan that calls for 20,000 acres of meadows restored[20]; and
- USDA Forest Service Region 5 Ecological Restoration Leadership Intent that calls for restoration of 50% of accessible degraded meadows in the next 15 -20 years[21].

## “All-lands, all-hands”

In this document, the Partnership sets forth an “all-lands and all-hands” approach with an overarching goal of restoring and/or protecting 30,000 acres on all lands in the Sierra Nevada. It proposes to refine this acreage through adaptive management. This ambitious goal was based on increasing the pace, scale, and efficacy of meadow restoration over current effort levels.

The Partnership chose an acreage higher than stated in the State Water Action Plan and the National Fish and Wildlife Foundation Sierra Meadows Restoration Business Plan in acknowledgement of the urgent need for increased meadow function. Attainment of this goal—which was felt to be challenging but feasible—would result in the restoration or conservation of one third of the currently degraded 90,000 acres of meadows in the Sierra Nevada, the Modoc Plateau, the Southern Cascades and Warner Mountains, which together comprise the “Strategy Area”.

The Partnership also chose a longer, fifteen year timeframe for this work because it believes that the target of restoring 10,000 acres in five years—as set forth in the State Water Action Plan—would only partly meet the overall need for restoration. The Partnership is confident that the restoration or conservation of 30,000 acres can be achieved within 15 years (circa 2030) and, moreover, that this critical work to improve the resilience of the Sierra Nevada and southern Cascades in the face of a changing climate **must** be accomplished within the fifteen year timeframe.

## Guidance for Practitioners

The intent of this Strategy is to help direct the Partnership and others involved in meadow protection, restoration and conservation to increase the pace, scale, efficacy, and benefits of meadow restoration and protection.

In order to achieve this ambitious plan of action, we have developed three guiding approaches that highlight desired conditions for restored meadows, and eight specific goals associated with those conditions. These form the basic tenets for practitioners to follow and which will also guide monitoring of the work.

## Approach 1

### Restore and/or protect meadows to achieve desired conditions.

GOALS

1. Desired conditions supporting the hydrologic and ecologic functionality of 30,000 acres of meadows are restored and protected.
2. Meadow soil resources that are most vulnerable to rapid and unrecoverable loss (e.g. peat soils found in fens and wet meadows) are protected.
3. Habitat conditions and ecosystem function for 30,000 acres are restored and/or protected to support populations of meadow dependent species representing multiple phylogenetic classes and that are currently rare, threatened or endangered.
4. Stressors affecting the health and integrity of meadows are mitigated.

## Approach 2

### Enhance regulatory and institutional funding capacity and coordination.

GOALS

5. Effective, efficient and coordinated regulatory requirements are established for restoring and protecting meadows.
6. Sufficient and broad-based funding sources are secured necessary for meadow restoration, protection and on-going monitoring and adaptive management.

## Approach 3

### Increase and diversify institutional and partnership capacity for meadow restoration and/or protection in the greater Sierra.

GOALS

7. Active participation of all-lands in meadow projects and increased capacity of landowners to fully participate in the designs, and implementation is increased.
8. State and regional water planning efforts reflect the key role meadow restoration can play in improving State water security.

Calistoga Meadows Workshop I participants, February, 2014. Photo: R. Kattelmann

Osa Meadow in the Sequoia National Forest—recently restored—is a long term study meadow. This picture shows the gullying that has degraded the meadow. Photo: M. Drew

This Strategy offers an opportunity to articulate and pursue common goals systematically and at scales ranging from meadow-specific to Sierra-wide. It is a living document developed by individuals involved in the Partnership and is intended to guide Sierra meadow protection, management, and restoration by describing desired conditions and by providing a roadmap towards these conditions. This roadmap includes a set of Approaches and associated actions, metrics, and outcomes, as well as a decision support framework. The geographic scope for the Strategy includes all of the Sierra Nevada, the Modoc Plateau, and the Southern Cascades of California. The Strategy has a greater footprint for downstream water users. The value of water flowing from federal, state and private lands has become increasingly important, especially where severe drought continues. More than half the state water supply flows from the Sierra Nevada and Southern Cascades.

This Strategy provides the guidance necessary to achieve an ambitious and effective course of action to increase rates of meadow conservation.

The content presented in the Strategy aims to identify a purpose, set of goals and a series of actions aimed at increasing the pace, scale and efficacy of meadow restoration. The three approaches, as described, are intended to address not only how to make positive change with respect to "on-the-ground" restoration, but also institutional change in terms of permitting, planning, funding and stakeholder involvement and partnership capacity. To achieve the target of restoring and protecting 30,000 acres in a 15 year period will require an all-hands, all-lands approach involving people, institutional change, improved coordination as well as perseverance. The Strategy is intentionally ambitious. However, a pathway does exist to increase the pace, scale and efficacy of meadow restoration throughout the broader Sierra Nevada.

**By reaching consensus on a path forward, a diverse group of agencies, scientists, and stakeholders can more effectively leverage necessary resources and the strategic changes required to increase the pace, scale and efficacy of meadow restoration and protection in the greater Sierra Nevada Region.**

**We invite all stakeholders to read the Strategy and join the Sierra Meadows Partnership in restoring and conserving meadows and their watersheds to provide and to restore a healthier and more resilient landscape within the next 15 years.**

# Section II

## Overview

## Purpose

The Sierra Meadows Strategy (Strategy) is a living document intended to guide Sierra meadow restoration, protection, and conservation (henceforth conservation), by describing desired meadow conditions and how the development and application of measurable objectives to achieve those conditions can facilitate rapid, integrated, and cost effective recovery of meadows and the services they provide. The shared vision of the Sierra Meadows Partnership is a greater Sierra Nevada region with healthy and resilient meadows that provide sustained goods and services to benefit flora, fauna and people. This document is intended as a decision support framework which supports and complements strategies developed by Federal and state agencies and other institutions involved in the broader meadow conservation effort (i.e. the State Water Action Plan; United States Forest Service Region 5 Restoration Strategy; and National Fish and Wildlife Foundation Sierra Nevada Business Plan).

## Sierra Meadows Strategy Structure

This Meadows Strategy offers an opportunity to articulate and pursue common goals using a systematic, scientific approach that can integrate across the Strategy Area, landscape, watershed and meadow scales. The Strategy provides guidance relevant to identification of healthy meadows, pre-restoration, restoration and post-restoration considerations as well as approaches to addressing institutional, permitting, funding, capacity and partnership needs and includes specific guidance on:

- Development of spatial prioritization for the Strategy Area to achieve landscape-scale desired conditions and desired outcomes;

- Development of watershed (e.g., HUC 12) and meadow-scale desired conditions;

- Development of objectives that support desired conditions and outcomes;

- Development of restoration and protection actions and adaptive management;

- Improved institutional, permitting and funding conditions and capacity necessary to increase the pace, scale and efficacy of meadow restoration;

- Next steps necessary to fully implement the Sierra Meadows Strategy.

## Sierra Meadows Defined

This Strategy offers a relatively inclusive definition of meadows developed from multiple sources[22-25]. In the simplest terms, meadows are defined by six hydrology, vegetation and soil characteristics. Meadows in the Sierra Nevada and Southern Cascades in California have these characteristics in common:

1. A meadow is an ecosystem type composed of one or more plant communities dominated by herbaceous species;

2. Meadows support plants that use surface water and/or shallow groundwater (generally at depths less than 1 yd.) during at least 2-4 weeks of the growing season;

3. Hydrologic sources include snowmelt, surface water from streams, and/or groundwater discharge near the land surface (generally at depths of less than 1 yd.);

4. Woody vegetation, like trees or shrubs, may occur and be dense but are not dominant;

5. Soils range from mineral soils to highly organic soils (peats);

6. Low stream gradients, if a stream channel is present, typically less than 2%.

## The Partnership

The Sierra Meadows Partnership first began very informally with the implementation of the National Fish & Wildlife Foundation's Sierra Nevada Meadow Restoration Business Plan[20] and has subsequently grown, particularly with respect to engaging an array of partners involved in meadow restoration in a more coordinated manner.

In February, 2014, a Sierra meadows workshop was convened in Calistoga, California with the intent of further enhancing coordination and developing a vision for Sierra meadow restoration moving forward. An outcome of "Calistoga 1" was the recognized need and development of an initial framework for a proposed "meadow strategy." Since the initial Calistoga gathering, there has been a focused effort on the part of many stakeholders to complete a Sierra Meadows Strategy, including three workshops convened at U.C. Davis and a second Calistoga workshop convened in February 2016 where more than 20 different entities actively participated in discussions that largely centered on developing the Strategy. It was during the "Calistoga 2" workshop that involved stakeholders decided to recognize the stakeholders involved as the Sierra Meadows Partnership.

Today, the Partnership comprises entities engaged in meadow protection, management, restoration and applied research to establish a common vision and approach necessary to increase the pace scale and efficacy of meadow restoration and protection in the greater Sierra Nevada region for the benefit of people and ecosystems. Consensus from the partnership on a path forward is reflected in this Strategy. Leveraging necessary resources and the strategic changes required to increase the pace and scale of meadow restoration and protection in the greater Sierra Nevada region is a shared goal of all.

Figure 1. The Sierra Meadows Partnership meeting in Calistoga in February 2016 brought the need and direction for a comprehensive Meadow Strategy into focus.

The shared vision of the Sierra Meadows Partnership is a greater Sierra Nevada region with healthy and resilient meadows that provide sustained goods and services to benefit flora, fauna and people.

The Sierra Meadows Partnership is a collaboration among interested stakeholders and has had participation by representatives  from non-profit and for-profit natural resource organizations (Plumas Corporation, California Trout, Trout Unlimited, Stillwater Sciences, Sierra Foothill Conservancy, Truckee River Watershed Council, American Rivers, The Nature Conservancy, Point Blue, Institute for Bird Populations, Occidental Arts and Ecology Center), public natural resource agencies (United States Forest Service [USFS], Pacific Southwest Research Station, National Park Service [NPS], United States Geological Survey [USGS]), Universities (University of California [UC] at Merced, Davis and Berkeley, University of Nevada Reno, California State University at Sacramento), and funding institutions (National Fish and Wildlife Foundation [NFWF], California Department of Fish and Wildlife [CDFW], and the State Water Resources Control Board [SWRCB]). At the time of writing, the Partnership is being broadened to include Resource Conservation Districts [RCDs], private and/or public funding entities, permitting agencies, and is open to new parties, including implementing groups and individuals interested in improving the ecological health of mountain meadows. The Partnership is open to all interested in supporting meadow restoration and management.

## Geographic Scope

The geographic scope for the Sierra Meadows Strategy, referred to as the Strategy Area, includes all of the California portion of the Sierra Nevada, the Modoc Plateau, and the Southern Cascades along with the Sierra and Cascade foothills and the Warner Mountains (see Figure 2).

While recognizing that there are meadows in other regions of California, this region is prioritized because of:

1. its shared legacy of impacts from grazing, railroads, logging, fire suppression, invasive plant and wildlife species, roads and recreation,

2. its shared central role in California water infrastructure,

3. its broad geography and relevance to USFS revisions to current USFS Sierra Nevada Forest Management Plans, and

4. the convenience of being geographically aligned with USFS (Sierra Nevada Forest Plan Amendment, generally referred to as the "Sierra Nevada Framework"), the Sierra Nevada Conservancy's Watershed Improvement Program and the National Fish and Wildlife Foundation Meadows Business Plan planning areas.

Figure 2.
The geographic scope, or Strategy Area, for the Sierra Meadows Strategy includes all of the Sierra Nevada, the Modoc Plateau, and the Southern Cascades, along with the Sierra and Cascade foothills and the Warner Mountains

# Section III

## Background

## Importance of Meadows: Derived Goods and Services

The Sierra Nevada–Southern Cascade Region is of great significance to the State of California. Comprising 25% of California's total land area, the region is California's principal water source, playing a critical role in California's water supply and hydrological system (Sierra Nevada Conservancy 2014). More than 60 percent of California's developed water supply originates in the Sierra Nevada, serving end users throughout the State[2]. In addition, the region contains a rich diversity of ecosystems, supporting 50 percent of California's plant species and 60 percent of California's animal species[2,26,27]. The region also provides world class recreational opportunities enjoyed by millions around the world.  Healthy meadows are important for local natural resource based economies supporting recreational, tourism, agricultural activities, among others[28,29].

Meadows cover less than 2% of the overall Sierra/Cascade landscape, but their unique hydrologic and ecological functions make meadows extraordinarily important. Fully functioning meadows add resiliency to the hydrologic and ecological processes that sustain California's headwaters, particularly during drought years which experts predict will be more common as climate warms[30,31,32]. Decreases in snowpack storage are expected to occur in the central Sierra Nevada particularly at mid-level elevations (2000 to 3000 ft. above MSL,33). Many meadows depend upon hydrologic inputs derived directly or indirectly from snowmelt[34] and bedrock stored groundwater[35] and could therefore, be vulnerable to effects of climate change[14]. However, the ability of meadows to store water from a variety of surface or subsurface sources makes them potential high elevation water storage alternatives to snowpack in the mountain landscape. In addition to water, healthy meadows can store roughly 1.5 to 2 times more soil carbon than degraded ones; however, higher carbon storage per unit area occurs in some meadows, such as fens, relative to others[36,37].

Healthy meadows can filter out sediment and pollutants, improving downstream water quality. Native meadow sedges have long and dense root and rhizome networks that are inherently resistant to erosion and that help maintain wet soils through much of the summer[38,39,40]. Healthy mountain meadows support these graminoid communities, while hydrologically altered meadows do not[41]. Channel banks occupied by sedge species erode much more slowly than channel banks supporting other vegetation[38]; thus these species help maintain the integrity and shape of the meadow channel and reduce bank erosion rates. With the smaller channel geometry common to functional meadows, high flows more frequently overtop the banks, allowing for percolation to subsurface storage, sediment and microbial filtering prior to the water re-entering the open channel[42,43].  By filtering out suspended sediment, healthy riparian vegetation builds stream banks and increase the seasonal quality of water released for downstream ecosystems and human uses[44,45,43].

Mountain meadows are key habitats for many Sierran animal species because they provide water and shade availability during the three to six month dry season, promote lower summer stream temperatures, higher plant productivity, increased insect prey availability, and special vegetation structures such as willow thickets[46]. Moreover, these ecologically rich oases often occur along riparian corridors, linking meadow to meadow and creating movement pathways across the broader landscape. The health and connectivity of these ecological corridors are critical for maintaining genetic diversity within species since these corridors facilitate interbreeding among populations and because they enable animals and plants to find new areas to inhabit. In the face of climate change and growing development pressures, these corridors can be lifelines for these species. The Sierra Nevada mountain range includes about two-thirds of the bird and mammal species and about half the reptiles and amphibians in the State of California[46,47]. During summer months, montane meadows are considered the single most important habitat in the Sierra Nevada for birds[46,47,48]. Meadows with streams that flow through them are also important habitat for native trout and other aquatic species[49], but are threatened by widespread warming[50].

The formation and maintenance of some mountain meadows may be due in part to actions of beaver (Castor canadensis)[51].  Beaver dams increase the vertical and lateral connectivity of rivers and streams, and associated floodplains that include mountain meadows. By raising the water table around dams, beaver increase the productivity of riparian and aquatic vegetation and help restore habitat for native species dependent upon functional meadows and associated channels.  Research from the Rocky Mountains illustrates the role beaver have played over thousands of years in alluvial sediment storage and formation of meadow landscapes and the long-term carbon storage provided by beaver ponds[52,53,54]. More studies are needed to understand the role of beaver in providing habitat, storing carbon, and providing an alternative approach to meadow restoration.

Meadows occur along a hydrologic continuum ranging from
a) dry meadows, which remain moist or wet in the rooting zone only for several weeks following snowmelt, to
b) wet meadows, which stay saturated at or near the surface for 1-2 months but can drop to moderate soil moisture levels later in season, to
c) fens, which typically remain saturated at or near the surface throughout the entire growing season and support organic soil.

Fens are peat-accumulating wetlands with a steady hydrologic regime, consisting of groundwater flow combined with surface flows such as snowmelt and/or streamflow, that allows them to remain saturated for most if not all of the growing season. The groundwater input to fens gives rise to unusual chemistry, which results in a highly diverse and distinct flora dominated by mosses, grasses, and sedges, but which also includes shrubs and trees[55,24]. In contrast, bogs receive water primarily from precipitation.  There are no bogs in California due to its semi-arid climate. These properties define existing meadows.

An altered meadow is one that once supported meadow vegetation as stated above but has been altered usually hydrologically or by other types of disturbance, so that the ecosystem no longer shares the six meadow characteristics listed above. While some of these alterations can be part of natural cycles (e.g. climate); most were induced by legacy land use. In this document, meadow degradation is defined as a loss of some or all in meadow forming and stabilizing processes that leads to reduced hydrologic and ecologic functionality of a meadow and hinders recovery.

## Extent and Current Status

The most recent estimate is that approximately 191,000 acres of meadow are distributed across nearly 17,000 meadows in the Sierra Nevada (Figure 2;[14,16]). Approximately 40-60% (77,000 – 115,000 acres) has been degraded and are in need of restoration[56-59]. Meadows are found on private and public land, including land owned by individuals, corporations, conservation organizations, and state and federal agencies. Approximately 28% of meadow acreage within the Strategy Area is under private ownership (see Table 1;[14,16]). With 46% of the meadow acreage on Forest Service lands, the USFS is by far the largest land manager of Sierra meadows, including the majority of small meadows and fens. The National Park Service is the third largest meadow land manager, with 22% of the meadow acreage in the Strategy Area (Table 1). Most of the remaining 4% is owned by local public entities and other Federal lands (Table 1). Thus, the responsibility for managing meadows is spread across various agencies and owners.


Osa Meadow with incised channel, one of the most common characteristics of a degraded meadow. Photo: L. Keszey

| **Jepson Regions** | **Total area (acres)** | **Number of meadows** | **Cumulative percent of total** | **Percent of area** |
|---|---|---|---|---|
| High Sierra | 147,028 | 15,227 | 77% | 77% |
| High Cascade | 21,181 | 1,024 | 88% | 11% |
| Modoc Plateau | 11,437 | 445 | 94% | 6% |
| Eastern Sierra | 8,571 | 216 | 99% | 4% |
| Sierra Foothills | 2,755 | 76 | 100% | 1% |
| Cascade Foothills | 44 | 9 | 100% | 0% |
| **Ownership** | | | | |
| USFS | 87,695 | 8,358 | 46% | 46% |
| Private | 53,935 | 2,123 | 74% | 28% |
| National Parks and Monuments | 41,738 | 6,380 | 96% | 22% |
| Local Public Ownership | 4,436 | 38 | 98% | 2% |
| Other Federal Lands | 2,516 | 32 | 100% | 1% |
| State Ownership | 696 | 66 | 100% | 0% |
| **Grand Total** | **191,017** | **16,997** | | **100%** |

## Legacy Impacts and Current On-going Threats to Meadows

In addition to conversion of meadows to other land uses during the last century (e.g., inundation by reservoirs, drainage for agriculture or development, roads etc.) 60 widespread disturbances to meadows have occurred throughout the Strategy Area. Disturbances, whether from human activities or natural causes such as fire, debris slide, or an extreme flood, can cause a cascade of events that can affect meadow function and the benefits meadows provide[61].

One of the most common characteristics of a degraded meadow is channel incision and/or gully creation. Incision can be caused by a number of different land use practices working alone or in combination. The most common sources of incision are channelization, construction of roads or railroads, ditching, overgrazing, and logging. Heavy livestock grazing contributed to the degradation of meadows during the late 19th century[62,63,55,15]. Changes to meadows attributed to legacy overgrazing include gullying, desiccation, conifer encroachment, and changes in plant species composition, structure, and diversity[64,55,8,63,65,15]. Today conditions and grazing-use patterns are improving; however, in some cases impacts from grazing are still occurring[66]. Grazing management permits cattle removal or reduction in seasonal use or numbers. However, once damage has occurred in a meadow it can be exacerbated by natural climatic variation, affecting meadow hydrology[67,68,69,34].

When stream channels in meadows become incised, or when a gully is created in a meadow with no pre-existing channel, the immediate effect is that water once stored in the rooting zone soil (primarily upper 1 yd.) drains down to the incised channel, lowering the water table and releasing subsurface groundwater from storage through the eroded channel or gully. This lowered water table has ramifications throughout the meadow, such as more rapid runoff and decreased meadow water storage capacity[70,71]. During the growing season, a lower water table effectively changes the hydrologic regime experienced by the vegetation; when these conditions persist and no longer support the existing plant communities, other species tolerant of drier conditions will thrive and eventually could dominate the affected areas. In highly organic “peat” soils, a lowered water results in microbial oxidation of the organic matter, which could eventually lead to land-surface subsidence[72].

Deeply incised channels and associated drawdown of groundwater can result in a destabilizing cascade of events: erosion channelizes flow and concentrates the erosive energy of floodwaters; down-cutting accelerates and, eventually the meadow surface, once a floodplain and recharge area during high flows, becomes a terrace; the terrace is cut off from the rewetting effect of seasonal floods; wet meadow vegetation is replaced by other drier vegetation types, with roots that are incapable of stabilizing streambanks; bank erosion is exacerbated, and the channel widens. Likewise tributary channels and swales incise to match the new, lower elevation of the main channel, and the result is a network of erosion gullies that drain the meadow. Such positive feedback among hydrologic, fluvial geomorphic and vegetative responses can exacerbate what may begin as a small perturbation, thereby hindering or preventing recovery without active restoration[61]. Thus, in many areas, meadows have been protected from grazing and other impacts for thirty years, but have still not recovered.

Long-lasting effects of soil compaction can also result in degraded meadow conditions, even where groundwater table elevations remain high[73-78]. Such effects include increased soil bulk density, reduced infiltration and water holding capacity and reduced root density. Soil compaction combined with selective grazing, can affect plant species composition by increasing the cover of grazing resilient species[73,63,79].

A changing climate and altered fire regime are also affecting meadow conditions in the Sierra Nevada. Fire suppression and an altered fire regime have resulted in both conifer encroachment[80,63] and hydrologic and sediment impacts associated with stand replacing fires in meadow contributing areas (e.g., scouring peak flows and large sediment deposits in the downstream meadow;[81,61]). Climate change is affecting the spatial and temporal distribution of snow vs. water in the Strategy Area[30]. Some parts of the Strategy Area are expected to have more reduced snowpack than others, and many areas are expected to see increased frequency of extreme events, including drought, rain on snow, and large peak flows[33,82]. Forest fires in contributing areas can combine with these shifts in weather and hydrologic patterns to generate very high peak flows and/or sediment deposits into the meadow channel and/or floodplain[14]. Healthy wet meadows, including fens, under saturated soil conditions, usually due to stable groundwater flows. These conditions are highly conducive to carbon accumulation over long time periods and the presence of unusual flora and fauna. The benefits from these meadows are particularly vulnerable to climate change. Fluctuations in snow and rain influence water availability and thus the saturated conditions essential for existence of these meadows and the benefits they provide[83].

# Restoration, Protection, and Conservation Defined

The term ‘restoration’ refers to implementation of one or more actions to improve meadow conditions or the discontinuation of activities that stress meadow conditions. These changes are directed at the processes and/or structures in the watershed or within the meadow itself that support meadow function[62]. Such actions or types of change may include:

1. actions at the watershed scale to improve and manage watershed and soil conditions (fuels and fire regime; roads and trails; connectivity of habitat; or grazing, development; or other land use practices to the extent they affect riparian vegetation or sediment and water flows to and within meadows) and
2. actions at the meadow scale to address, improve, and manage hydrologic and geomorphic process and associated structure (channel condition, channel floodplain interactions, bank condition, etc.), vegetation structure and condition, wildlife habitat and species population condition and or the suite of services (range forage, recreation, etc.) meadow systems support.

In this document, the term ‘restoration’ is used to refer not only to actions intended to ‘return’ the meadow to the un-disturbed pre-EuroAmerican influence conditions (in itself a challenging target to identify), but also to actions that enhance existing processes and structures in the meadow to move the meadow closer to what has been identified as the ‘desired conditions’. Desired conditions may or may not reflect best estimates of a particular meadow’s condition under pre-EuroAmerican conditions; but could rather reflect what is considered to be the best possible functional state given the current and projected future trajectory or key parameters.

Sierra meadow protection and management are wrapped up together. The health of the watershed influences the health of the meadow or meadow complexes in the watershed.  While watersheds in good condition may be functioning well, they need to be evaluated for future changes as warming or extended drought occur. Prioritization based on biodiversity of Species of Conservation Concern may also be used to drive protection and preservation. The protection of a meadow or a fen may entail taking steps to prevent erosion within the meadow, taking steps to protect and manage the watershed (upper watershed) for resilience to fire and future hydrologic changes. It may involve active management or allowing natural processes to occur. Sierra meadow protection, management, and restoration is referred to as “conservation“ in this document. Restoring and maintaining healthy meadows that provide multiple benefits requires long term engagement and a perspective that sees meadow functions at site to landscape scales. Meadow conservation over the long-term requires incorporating the anticipated trajectory of a meadow and its supporting landscape, where the trajectory includes future pressures from climate change, human use, invasive species, and land use change.
Conservation requires long-term engagement through monitoring before and after initial actions, and adaptive management in response to monitoring observations and changing conditions. Ideally, long-term funding to support monitoring and adaptive management is built into all restoration project funding packages, as is adequate funding to monitor and adaptively manage effects of restoration at watershed and landscape scales.

For more information on restoration in meadows, examples of different types of restoration actions that have been used at the time this strategy was developed, and lists of information sources on restoration actions, see Stillwater 2012 and Norman 2015, and the U.C. Davis Meadow Clearinghouse (http://meadows.ucdavis.edu/projects).

Upper Sardine Meadow.  Photo: H. Drew

# Guiding Principles

The Sierra Meadows Partnership participants recognize a number of important principles that will help guide successful implementation of this Strategy. These are broadly described in this section.

## Successfully increasing the pace, scale, and efficacy of meadow conservation will require a holistic approach that addresses:

1. Natural, biophysical and social sciences,
2. Policy/permitting,
3. Funding/investment,
4. Reaching across land boundaries,
5. Capacity building, and
6. Political support.

While we have emphasized the biophysical and natural roles played by meadows, we recognize the importance of these iconic places to human socioeconomic as well as human-ecological interactions. The broad and diverse Sierra Meadows Partnership can assist in developing capacity, working with regulators and funders, and build upon the convergence of support across the State.

In developing plans to implement meadow conservation at broad scales, it is best to use a scientifically based and structured approach to move from identifying desired conditions to achieving outcomes. Where meadows and their watersheds are functioning well, they can be identified as areas for protection. This protection may mean active management of activities within the watershed or reliance on natural processes to maintain the meadows.  Specifically, desired conditions can be clearly articulated through specific, measurable, achievable, relevant, and time bound (SMART) objectives and associated metrics. Actions can be designed to achieve objectives (e.g. provide flow access to 50 - 100 percent of old floodplain), and outcomes (e.g. improved meadow condition, recovered plant community.) These metrics can be evaluated against desired conditions and adaptively managed based on the extent to which they achieve outcomes. In all instances, participants should strive to use and contribute to the best available scientific information (BASI). At each step in project development and implementation, multiple scales should be considered such that strategies, objectives, actions and measurements of outcomes can be understood at the scale of the individual meadow, the watershed (~HUC12), province/mini-region, and the Strategy Area. Moreover, ecosystem service production is an effective means of indicating meadow function where the linkage between function and service is well understood (e.g., increased groundwater storage or increased downstream water quality). This is based upon the recognition that ecosystem services are provided by functioning ecosystems.

## Conservation is undertaken through a series of phases:

1. Pre-restoration site assessment,
2. Assessment of sources of stress, limiting factors and constraints on natural vs. assisted recovery,
3. Development of measurable objectives,
4. Planning, design and permitting,
5. On-the-ground restoration,
6. Post-restoration monitoring, and
7. Adaptive management over the short and long term.

These conservation actions should be designed to allow natural processes to develop and maintain dynamic meadow ecosystems, rather than focus on building or maintaining a static system (e.g., use remnant channels where possible rather than constructing or armoring channels that do not move; allow for beaver activities to effect channel migration and local ponding). Diverse restoration and/or enhancement methods can be applied, as tailored to site-specific conditions, and new ideas and methods should be encouraged and systematically monitored to compare and optimize for the most effective methods for the range of conditions, site histories, geographic locations, and institutional capacities. We suggest that restoration be implemented using multiple tools and using adaptive management of activities in watersheds across the Strategy Area to include both private and public lands.

Once a meadow has been restored, it will need to be adaptively managed along with other functioning meadows to ensure that the benefits to wildlife, plants, recreation, grazing and downstream water users are provided over the long term. In addition, practitioners should recognize and adapt to changing conditions and their effects on meadow processes (e.g. climate change effects on hydrologic regime). In this way, meadow conservation should provide for resilience and adaptability to climate change.

# Section IV

## Desired Conditions and Associated Goals

The desired conditions and associated goals described in this section apply to the Strategy Area as a whole and are intended to (1) guide and track the overall success of the Strategy and (2) guide development of finer-scale desired conditions, objectives, actions, and outcomes. The desired conditions describe conditions we would like to have achieved within fifteen years, both ecologically and for human use and management; while the goals provide a set of quantitative targets we need to meet in order to build this future together.

## Desired Conditions

The desired conditions are broadly defined outcomes for the Strategy Area. These can be further refined and specified for watershed and project scale planning. We used desired conditions drafted by Region 5 of the Forest Service as a starting point (basis for desired condition found in USDA Forest Service 2014, and draft plans at http://tinyurl.com/r5earlyadopters). The Meadows Partnership members refined and elaborated upon the draft Forest Service text and ultimately agreed upon the Desired Conditions described below:

### Meadows are diverse and complex.

- Meadows often include a mosaic of habitats and successional plant communities that support native plant and animal populations. Meadow species composition is predominantly native, where graminoid species are well represented and vigorous, and regeneration occurs naturally. Ground cover is resilient, protecting against erosion. Species composition is diverse, recognizing that species composition and diversity are dependent on both hydrologic conditions and disturbance factors. Natural processes, including disturbances, and management activities are sufficient to maintain desired vegetation structure, species diversity, and nutrient cycling. Healthy stands of willow, alder, and aspen are present within and adjacent to meadows where they would naturally occur. Meadows with perennial streams contain a diversity of age classes of hardwood shrubs along the stream bank, where the potential exists.

- A diversity of healthy meadow types exists, including types that are dependent on water inputs to create wet rooting conditions from surface, subsurface, or groundwater, throughout the growing season, through mid-summer, or only in the early spring[25]. These types occur on different geomorphic surfaces, such as alluvial fans, terraces and floodplains, local depressions, and lake edges, and include meadows that act as ground water recharge areas and as surface water source areas. The range of meadow types are well distributed according to their potential in the Strategy Area and support diverse soils and plant community types.

- Meadows support diverse native plant, terrestrial and aquatic animal species, including aquatic species dependent upon cool and high quality water flows in downstream reaches.

### Healthy watershed and meadow hydrology and geomorphology are intimately linked and well understood.

- Meadows are depositional features in the landscape with fine textured mineral or organic soils, where sediment and water from the contributing area are temporarily stored (for short periods to 1 to 10s to 100s and 1,000s of years) as these elements migrate downslope. Meadows typically exhibit a high degree of hydrologic connectivity, both laterally across the floodplain and vertically between surface and subsurface flows. Depending on their particular hydrology, meadows can provide important ecosystem services such as high quality water purification and groundwater recharge. Meadows are resilient and recover from natural and human disturbances. Meadows buffer the downstream effects of large fluctuations in sediment and water input from upslope areas, thereby ameliorating effects of increased climatic variability on downstream resources.

- The hydrologic, edaphic, and other needs of wet and headwater meadows, such as fens, are well understood and maintained to ensure that these unique meadow types and their dependent plant and wildlife species are supported, fully functional, and resilient to variations associated with climate change. Soil in these meadows can accumulate organic matter and are spongy and moist, generally as a result of a shallow water table which slows litter decomposition in relation to plant growth and litter production. Such soils have high water holding capacity and function to filter, store and release water over an extended period of time. Wet meadows with highly organic soils may continue to accumulate organic material in their soil for hundreds and thousands of years[83] and therefore be net long-term carbon sinks. The balance between organic matter accumulation in the soil and emission of wetland associated greenhouse gases (e.g., methane and nitrous oxide) into the atmosphere has been determined over multiple years and for a range of wet meadow types. Unusual water and soil chemistry in meadows supporting highly organic soils that receive important amounts of water from groundwater sources (e.g., fens) host unusual plant species and are protected to support landscape beta diversity[83,84].

- The role of beaver in creating dynamic meadow habitat for flora and fauna is well understood and non-lethal solutions to beaver management are in widespread use.

- The watersheds are resilient to climate changes including prolonged drought, changing patterns of precipitation, and warmer conditions. Insect outbreaks, increased risk of severe fire, severe erosion, and tree mortality are minimized through active management of watersheds.

### Meadow Protection and Enjoyment

- Meadows are protected from development where important ecological resources are threatened.

- Meadows and streams support recreational uses of such as fishing, hunting, bird and butterfly watching and wildflower viewing.

- Natural resource management institutions and practitioners manage human actions and natural resources that affect meadows in a coordinated, pro-active way that supports and maintains fully functional watershed and meadow processes and physical conditions. Interactions among institutions, including implementation of regulations intended to protect natural resources, are coordinated, transparent, effective and efficient to protect and also support timely restoration and/or enhancement actions.

- Land owners and land managers across the Strategy Area are engaged in meadow management and restoration and have easy access to the most recent information and resources—including sources of financial support—and expertise in meadow management, restoration, and restoration effectiveness monitoring.

## Sierra Meadows Strategy Goals

The goals are broadly defined for the Strategy Area. These can be further refined and specified for watershed and project scale planning. These eight goals are intended to guide development of finer scale SMART objectives that are described in Section V. An assumption underlying these goals is that the Strategy will lead to an increase in the pace, scale and efficacy of meadow restoration, management and protection.

In addition, these goals:

- Are intentionally broad and use correspondingly broad metrics which can be assessed at the landscape level and refined for a project. These goals will lend themselves to region wide assessments of the role and advancement of meadow restoration;

- Will be updated approximately every two years;

- Are not listed in order of importance;

- Are inter-related, so that achieving one will require achieving others;

- Address not just restoration, but also continued management and protection of meadows;

- Will require implementation of three Approaches (detailed in Section V):
    - On-the-ground restoration and conservation management to achieve and maintain desired conditions; and increase the pace of meadow restoration;
    - Enhancement of regulatory and institutional coordination; and
    - Increased capacity and partnership opportunities.

A solid foundation of partnerships among land managers, advocacy groups, restoration practitioners, land trusts, and research institutions exists, and these partnerships have been critical to realizing the restoration of approximately 10,000 acres of montane meadow to date[85]. This Strategy aligns with

- the State Water Action Plan[18],
- the Sierra Nevada Watershed Improvement Program Regional Strategy[19],
- the National Fish and Wildlife Foundation Sierra Meadows Restoration Business Plan[20]; and
- the USDA Forest Service Region 5 Ecological Restoration Leadership intent[85].

California's State Water Action Plan calls for 10,000 acres of meadows to be restored[18]. US Forest Service Region 5 Ecological Restoration Leadership Intent[86] calls for restoration of 50 percent of accessible degraded meadows in the next 15 to 20 years. The Watershed Improvement Program supports restoring and protecting the health of Sierra Forests and acknowledges that significant effort will be required to restore meadows, since their health is critical to stream condition as well as downstream water quality[19]. The NFWF Sierra Meadow Business Plan called for 20,000 acres of meadows restored prior to 2014[20].

To increase the pace and scale of meadow restoration in the Strategy Area, we chose an acreage target that is higher than that of the State Water Action Plan and the NFWF Sierra Meadow Restoration Business Plan, and less than that of the estimated 90,000 degraded meadow acres in the Strategy Area[14]. Thus, the Strategy sets forth an "all-lands and all-hands" approach with an overarching goal of restoring and/or protecting 30,000 acres on all lands in the Sierra Nevada and proposes to refine this acreage through further analysis over time. The overarching goal was based on increasing the pace, scale, and efficacy of meadow restoration. The Sierra Meadows Partnership chose an acreage higher than the State Water Action Plan and the NFWF Sierra Meadow Restoration Business Plan to support significant increases in pace, scale and efficacy over current effort levels, recognizing both that this target is challenging but feasible, and the urgent need to achieve increased meadow function. Achievement of this goal will result in the restoration or conservation of one third of the currently degraded 90,000 acres of meadows in the Sierra Nevada, the Modoc Plateau, the Southern Cascades and Warner Mountains, which comprise the "Strategy Area"[14]. The Partnership chose a fifteen year time window based on several factors. The target of restoration of 10,000 acres in five years set forth in the State Water Action would only partly meet the overall need for restoration. The Partnership believes that the goal of restoring approximately one third of the degraded meadows can be achieved within 15 years (circa 2030) and that this critical piece of improving the resilience of the Sierra Nevada and southern cascades to our changing climate must be accomplished within the 15-year timeframe.

This will be accomplished through a combination of protecting currently functioning but threatened meadows, and by enhancing and/or restoring degraded meadows. Those that currently or potentially provide critical hydrologic, edaphic, and/or biodiversity benefits should be prioritized.

The following goals are more specific to ecosystem function, vulnerability, species, climate and other stressors, regulatory and funding requirements, participation of all lands, and contribution to the overall water supply in California.

### GOAL 1

## Desired conditions supporting the hydrologic and ecologic functionality of 30,000 acres of meadows will be protected and restored (according to the conditions as described).

Emphasis to be landscape-scale, supporting downstream resources for humans and native species (e.g., supporting biological diversity through recovery and protection of native meadow and river-dependent aquatic, avian, plant and other wildlife species).

### GOAL 2

## Protect from threats those meadow soil resourcesthat are most vulnerable to rapid and unrecoverable loss (e.g., such as peat soils found in fens and wet meadows).

Threats include those ssociated with climate change, land use change, and/or human manipulation of upstream and downstream water resources. Protection means that soils and native vegetation are intact within the next fifteen years.

### GOAL 3

## Habitat conditions and ecosystem function for 30,000 acres are restored and/or protected to support populations of meadow dependent species representing multiple phylogenetic classes and that are currently rare, threatened or endangered.

This is designed to support the broader goal of those populations being substantially recovered within the next fifteen years, with the recognition that recovery for those populations may hinge on conditions beyond what can be achieved through meadow restoration. Meadow type, location and connectivity in the landscape is protected and restored to support recovery of native meadow dependent species and downstream rare aquatic species. Protecting and expanding upon existing habitat and targeting areas which serve as critical landscape links among existing populations will support large and genetically robust populations of meadow and stream dependent species throughout their potential range.

### GOAL 4

## Stressors affecting the health and integrity of meadows are mitigated.

The existing and future potential distribution of meadow resources (including hydrology, biodiversity and soil resources) and their overlap with current and future stressors (including climate, fire, land use change, water use infrastructure, grazing, and invasive species) is well articulated.

### GOAL 5

## Effective, efficient and coordinated regulatory requirements are established for restoring and protecting meadows within the next fifteen years.

Land management agencies (NPS, USFS, BLM, USFWS, CEDFW and State Parks) and Partnership parties provide training, resources and collaboration to support regulatory compliance under NEPA and CEQA to facilitate actions under the “all-hands-all-lands” approach. The necessary resources for regulatory compliance include sufficient budget for in-house labor, permit costs, and expertise required to perform surveys and assess findings. Within the next fifteen years, agreements are put in place among land management and regulatory agencies that ensure that the regulatory requirements for protecting and restoring meadows are met in an effective, efficient and coordinated manner.

### GOAL 6

## Sufficient and broad-based funding sources are secured necessary for meadow restoration, protection and on-going monitoring and adaptive management.

### GOAL 7

## Active participation of all lands in meadow projects and increased capacity of landowners to fully participate in the designs, and implementation is increased.

### GOAL 8

## State and regional water planning efforts reflect the key role meadow restoration can play in improving State water security.

Existing and future versions of the State Water Action Plan and Integrated Regional Water Management Plans) acknowledge the Sierra Nevada and it associated ecosystems as an important element of California’s water infrastructure and by extension the key role meadows could play in improving California water security.

# Section V

## Guiding Approaches

The Sierra Meadows Partnership developed three overarching approaches to achieve desired conditions and associated goals (Section IV). The three approaches focus on (1) restoration of meadows to desired conditions; (2) enhancing regulatory and institutional funding capacity and coordination; and (3) increasing and diversifying institutional and partnership capacity. These pproaches are intended to be implemented simultaneously and will need to be in order to achieve the stated goals of the Sierra Meadows Strategy. These approaches are also meant to complement already existing efforts to advance meadow restoration and management within the Sierra Meadows Strategy Area. It is acknowledged that in some areas, actions identified in one or more of the approaches are already being implemented.

## Approach 1

### Restore and/or protect meadows to achieve desired conditions.

Focus on implementing the 8 steps of a successful meadow restoration project (See Figure 3 on the next page): pre-restoration monitoring; development of restoration needs to bring meadows to desired conditions; development of measurable objectives; design based on objectives and needs; compliance and permitting; on-the-ground restoration implementation; post-restoration monitoring; and adaptive management. Meadows in good functioning condition identified in pre-restoration monitoring would be monitored and adaptively managed in a manner consistent with restored meadows. A key component of this approach is to use clear measureable objectives tied to effectiveness monitoring that can then trigger (require) adaptive management.

## Approach 2

### Enhance regulatory and institutional funding capacity and coordination.

Identify and alleviate regulatory bottlenecks and establish efficient and respectful communication pathways. Field visits and knowledge gleaned from earlier restorations can be used to assist in building a good working relationship among regulators, restoration specialists and land managers. Ensure funding meadow restoration and monitoring is a priority at the state and federal levels.

## Approach 3

### Increase and diversify institutional and partnership capacity for meadow restoration and/or protection in the greater Sierra.

Institutional and public outreach, including schools, colleges, Integrated Regional Water Management groups, state and county agencies can broaden the base of support and understanding of the value of restored Sierra meadows. Assist in establishing priorities for restoration based on Species of Concern or other priorities.

## Approach 1

### Overview

This approach focuses on actions taken on the ground to improve meadow health, function and resilience. This approach is designed to function at the Strategy Area scale and at smaller scales to allow watershed, Forest or site-specific meadow characteristics and processes to come into focus. Thus, scales can range from a single meadow to a series of meadows in a watershed.

This approach also addresses protecting meadows from conversion to urban development or other incompatible land uses (gravel mining, golf course, roads, other). Meadows are targeted for protection based on their value for biodiversity, threatened and endangered species, or rare species, ecosystem services, or restoration potential at a landscape scale.  Threats, known as well as based of future assessments, to meadows in terms of land development pressure are considered in prioritizing locations for meadow protection to accomplish the desired outcomes below.

Steps for achieving restoration to desired conditions are outlined in Figure 3. These steps are meant as guidance rather than a required set of actions. Their primary intent is to ensure that meadows are targeted for restoration and/or protection based upon a landscape scale assessment of needs and opportunities to most efficiently and directly achieve the Desired Outcomes described in Section IV above.

As shown in Figure 3 (next page), identifying desired conditions and assessing current conditions relative to desired conditions serves as the basis for determining restoration needs. Once needs have been identified, identification of SMART objectives (Specific, Measurable, Achievable, Realistic and Timely) serves as the foundation for developing a given restoration project/action and in doing so will help to identify which permits may be required and any associated compliance obligations.

Obtaining necessary permits then provides the trigger for implementing actions and subsequently monitoring the effects of such actions to determine if objectives are being met and ultimately if desired outcomes are realized, or, whether further adaptive management actions are necessary. As an example, restoring hydrologically degraded meadows could yield the desired outcomes of expanding and protecting habitat connectivity for a listed meadow-dependent species such as the willow flycatcher. Meadows within the area would be assessed based on existing desired conditions for that hydro-geomorphic meadow type/ area/ watershed.

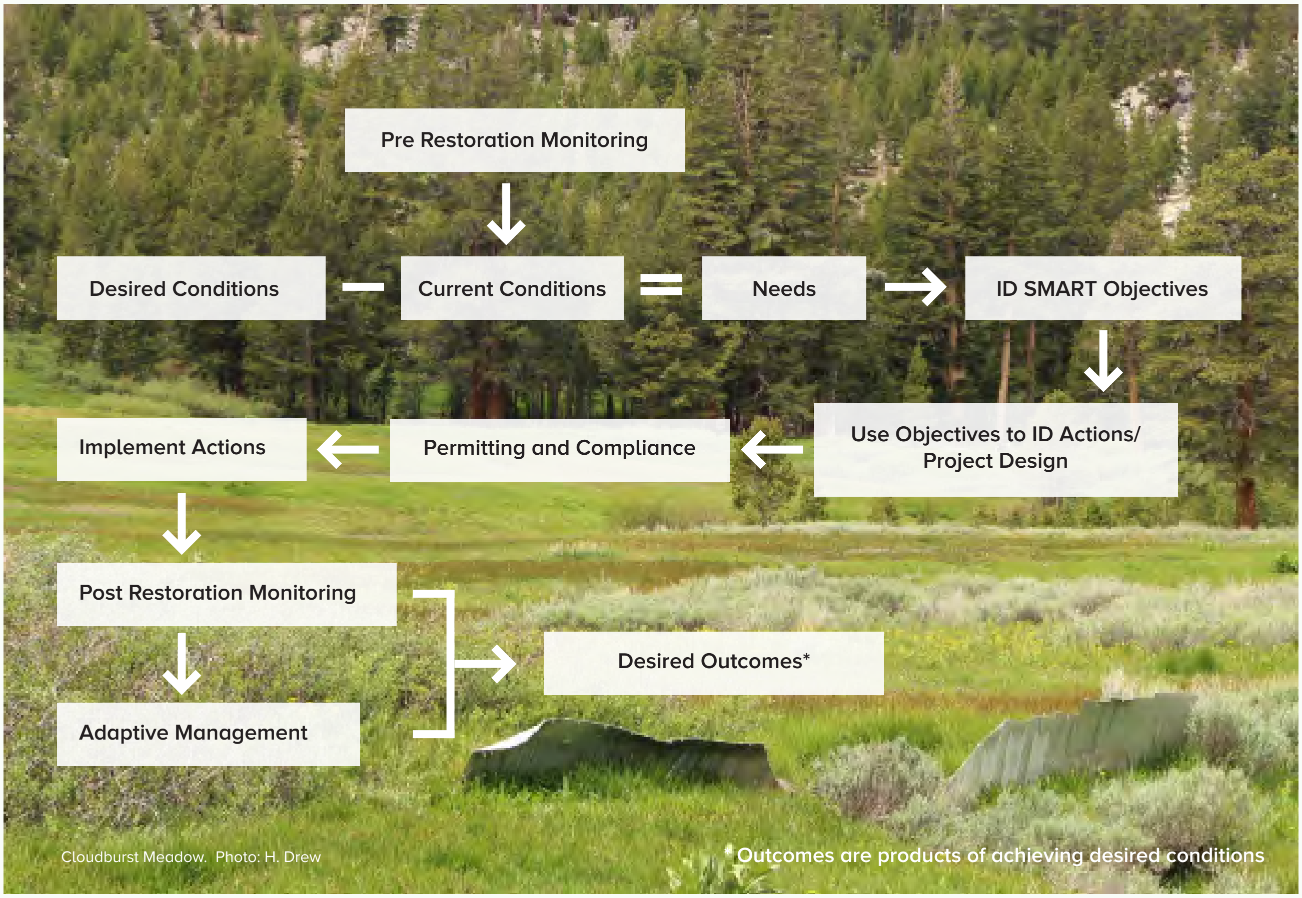
Landscape and site-specific information (such as contributing area hydrology, species presence and potential, geology, climate and soils) and current and future threats and opportunities (e.g., climate change, fire, and invasive species) would be integrated to create as set of SMART objectives for meadows in the target area. A conservation design for meadows in that area should help meet those SMART objectives. Restoration actions would then be implemented through the next phases of implementation and post implementation monitoring/adaptive management.

## Desired Outcomes, Actions and Milestones

A set of desired outcomes, necessary actions and milestones for Approach 1 are provided in Tables 1-3 below. These are presented as short-term (to occur within next five years), intermediate-term (to occur within next ten years), and long-term (to occur within the next fifteen years) actions. The fourth column indicates whether the actions are expected to occur at the local (W for watershed) or regional (R) scale. In this case, watershed refers to approximately HUC12 size watersheds or HUC10 and regional stands for the Strategy Area (Figure 2).

Short term desired outcomes include refining our understanding of existing conditions; identifying and addressing critical information gaps; articulating desired conditions; identifying priority meadows for action; and prioritizing meadows for conservation and adaptive management. Intermediate desired outcomes include achieving continued meadow restoration and protection over the next 10 years; and monitoring and evaluation to support improvement of meadow functionality. Long term desired outcomes include monitoring restored meadows to adaptively manage them; evaluating whether restored meadow functionality closely approaches desired conditions; evaluating whether restored meadow functionality is resilient across the range of water year types (reduced vulnerability); and evaluating whether benefits to biodiversity, hydrology, soils, and carbon storage are being achieved.

## Using SMART Objectives to Achieve Desired Outcomes



Cloudburst Meadow. Photo: H. Drew

*Outcomes are products of achieving desired conditions

Figure 3. Flowchart of the steps for achieving restoration to desired conditions and outcomes.

## Approach 1: Short-term Plan

Desired outcomes, actions and milestones to restore and protect meadows to achieve desired conditions.

| Desired Outcomes | Actions | Milestones | W/R |
|---|---|---|---|
| **Critical information gaps identified and addressed** | Develop methodologies for measurement/monitoring of greenhouse gases and carbon sequestration in meadows. | Demonstrated effective methodologies for measurement/ monitoring of greenhouse gases and carbon sequestration in meadows available for use (white paper). | R |
| | Research carbon cycling in variety of meadows to determine net carbon balance and whether they have a positive, negative, or neutral global warming potential. | Research projects successfully executed; peer-reviewed publications on findings; critical information gaps identified and filled. | R |
| | Determine needs for ground validation of landscape level and remote sensing data used to map wetlands. | Methodology developed for incorporating individual wetland delineations (soils, hydrology, & vegetation/plants) into meadow database. | R |
| | Determine best methods for assessing aquatic, plant, and wildlife use and habitat condition. | Have one validated methodology to allow for comparisons among sites. | R |
| | Develop guidelines for definition and management of riparian areas around meadows based on BASI. | Riparian Management updated to include use of fire or other techniques that are consistent with managing for all species. | R |
| | Develop an approach to restoring Yosemite toad habitat in meadows with USFWS and interested stakeholders. | A plan to allow meadow restoration in occupied habitat for Yosemite Toad will include a Programmatic Biological Opinion for restoration within each designated critical habitat and/or occupied areas for Yosemite Toad. | R |
| | Based upon other reports and project products (e.g., listed as other actions above), summarize key information gaps for soils, hydrology and biodiversity including landscape and site scale structure and processes. | Report summarizing key information gaps limiting understanding needed for restoration of meadow hydrology, soils and biodiversity. | R/W |
| | Secure funding to fill critical information gaps. | Reports that cross-tabulate with set of information gaps identified in action above and associated funding in-hand vs. funding needs. | R/W |
| | Perform studies to fill gaps to describe existing conditions in each focus meadow for soil, hydrology and biodiversity. | Report summarizing condition of each focus meadow using consistent methodology and set of metrics (landscape and site scale). | W |
| | Perform studies to fill gaps on meadows for soil, hydrology and biodiversity at landscape and regional scales. | Report summarizing conditions for meadow soil, hydrology and biodiversity at landscape and regional scales. | R |
| **Desired conditions articulated** | Develop desired conditions and associated SMART objectives for hydrology and soils by Weixelman type as at least one framework. | Report summarizing desired conditions by Weixelman type for soils and hydrology. | W/R |
| | Develop desired conditions and associated SMART objectives for biodiversity (including aquatic and terrestrial wildlife and plants). | Report summarizing desired conditions for biodiversity by Weixelman Meadow type and location. | W/R |
| | Select indicator species and associated SMART objective based on meadow types, location, connectivity issues, species range and potential responses of the species to meadow conservation. | Report summarizing desired conditions for selected indicator species. | W/R |
| | Develop desired conditions in terms of number of meadows or acres of meadows that need protection to provide adequate habitat and ecosystem service provision. | Report summarizing state of meadows relative to desired conditions. | W |
| | Update and refine desired conditions according to new information as it comes in or at least every 3 to 5 yrs. | Updated reports, every 3-5 years. | W/R |
| **Priority meadows for action identified** | For region, identify priority watersheds (HUC 12) for meadow restoration using Weixelman types, focal species, and vulnerability assessments (e.g., climate and land use change, limiting factors analyses) and beaver dam building habitat model. | Prioritization of HUC 12 watersheds with explanation and rational for methods for focal species, soils (carbon), and water storage and delivery, and with description of critical information gaps. | R |
| | Secure funding to perform spatial analysis of meadows to determine extent of known information, information gaps, and assist prioritization of future meadow restoration, protection etc. | Funding secured. | W |
| | Articulate feasibility issues for each meadow. | Feasibility assessment for each meadow. | W |

Table 1. Fourth column indicates local watershed (W) or regional scale (R)

## Approach 1: Short-term Plan, Cont.

Desired outcomes, actions and milestones to restore and protect meadows to achieve desired conditions.

| Desired Outcomes | Actions | Milestones | W/R |
|---|---|---|---|
| **Priority meadows for action identified** | Assess potential benefits or effects of restoration on each set of resources for each meadow at site and landscape scales. Evaluate whether these benefits will achieve desired conditions. | Landscape and site scale assessment of possibility of achieving desired conditions for each meadow. | W |
| | Identify meadows important for biodiversity, threatened and endangered species, rare species, climate refugia, connectivity, and ecosystem services. Overlay important meadows with development pressure to determine priorities. | Meadow spatial analysis completed with priority ranking based on biodiversity and ecosystem services. | R/W |
| | Prioritize meadows for restoration. | Annotated list of priority meadows for restoration (watershed or landscape). | R/W |
| **Priority meadows restored and adaptively managed** | Secure funding for pre- restoration monitoring and initial project designs. | Sufficient funding to perform pre-restoration monitoring and initial project designs available to practitioners. | W |
| | Develop restoration, monitoring and adaptive management plans for high priority meadows. | Complete restoration, monitoring and adaptive management plans. | W |
| | Perform pre-restoration monitoring to establish baseline for soils, hydrology, and biodiversity at site and landscape scales. | Pre- restoration monitoring reports. | W |
| | Report on landscape scale conditions or processes that currently protect, impact, improve or depend upon meadow function for target meadow (both above and below). | Landscape scale condition report or section of existing conditions report. | W |
| | Refine and revise, as needed, restoration design based on findings of pre-restoration monitoring. | Refined restoration design as needed. | W |
| | Secure funding for permits, implementation, monitoring, and adaptive management. | Funding sufficient to perform permitting and full implementation, monitoring, and adaptive management. | W |
| | Secure necessary permits and address compliance obligations. | Necessary local, state and federal permits; Compliance obligations addressed. | W/R |
| | Implement restoration actions. | Number of projects successfully implemented. | W |
| | Post-project effectiveness monitoring to assess restoration actions relative to established objectives and desired conditions. | Evaluation of the project to meet desired conditions and outcomes. | W |
| | Based on post-project monitoring findings, design adaptive management actions as needed. Priority meadows. | As needed, adaptive management actions are identified to achieve desired conditions. | W |
| | Subject to permitting, compliance and funding, implement adaptive management actions. | Adaptive management actions implemented. | W |

Table 1, Cont. Fourth column indicates local watershed (W) or regional scale (R)

## Approach 1: Intermediate-term Plan (5-10 yrs., or by 2020-2025)

Desired outcomes, actions and milestones to restore and protect meadows to achieve desired conditions.

| Desired Outcomes | Actions | Milestones | W/R |
|---|---|---|---|
| Continued meadow restoration and protection achieved | Restore remaining unrestored priority meadows and adaptively manage all meadows in need of protection. | List showing percentage of priority meadows that have undergone restoration and on-going adaptive management. Evaluation of the achievement of objectives with previous restorations, if needed propose additional adaptive management actions in watershed. | W |
| | Integrate knowledge gained through recent studies and restoration projects into additional meadow restoration actions. | Report with an evaluation on the effectiveness of restoration actions in achieving goals and objectives. Evaluation of recent studies of restoration actions and/or monitoring reports and with any necessary suggested changes to designs for future restorations and adaptive management actions. | W |
| Monitoring and evaluation to support improvement of meadow functionality | On-going measurement of net soil carbon storage in restored meadows and representative subset of protected meadows with soil carbon storage as a component of the greater functioning ecosystem observed in reference meadows. | Report on 2 to 5 year post-restoration measurements of GHG flux and net change in soil carbon reservoirs in restored meadows compared to pre-restoration measurements to determine if desired conditions are being met; development and implementation of adaptive management plans if not being met. | W |
| | On-going monitoring of floodplain and ground water connectivity at site scale where restoration has targeted increased connectivity in ground and surface water. | Report on 2 to 5 year post-restoration measurements of meadow groundwater levels and surface water flows to indicate whether or not desired conditions are being met according to water year types; development and implementation of adaptive management plans if not being met. | W |
| | On-going monitoring of habitat conditions known to support focal plant and animal species compared to pre-restoration conditions. | Report on 2 to 5 year post-restoration measurements of meadow habitat conditions for key focal species to test whether or not conditions are significantly improved compared to pre-restoration conditions; development and implementation of adaptive management plans if not being met. | W |
| | Monitor population or occupancy of key focal fish, amphibian, bird, wildlife and plant and animal species compared to pre-restoration conditions. | Report on 2 to 5 year post-restoration occupancy or population trends for key focal species to test whether or not conditions are significantly improved compared to pre-restoration conditions. | W |
| | Develop an annual report for partners to share work currently underway as well as accomplishments. | Report on monitoring, assessment, evaluation of SMART objectives, restoration and other work underway across the Strategy Area. Summarize more technical reports for a more general audience. Post/distribute findings. | R |
| | On-going monitoring of flows and stream temperatures downstream of restored meadows to determine restoration effects on their dynamics. | Report on 2 to 5 year post-restoration measurements of stream flows and temperatures to determine whether or not desired conditions are being met according to water year types and season; development and implementation of adaptive management plans if not being met. | W/R |

Table 2. Fourth column indicates local watershed (W) or regional scale (R)

## Approach 1: Long-term Plan (in 15 yrs.)

Desired outcomes, actions and milestones to restore and protect meadows to achieve desired conditions.

| Desired Outcomes | Actions | Milestones | W/R |
|---|---|---|---|
| **Restored meadows are monitored and adaptively managed** | Hydrologic monitoring of surface and groundwater at meadow scale. | Reports and data available on ground and surface water flows. | W/R |
| | Hydrologic monitoring of channel flows upstream and downstream of meadow | Reports and data available on surface water flows and/or weather data. | W |
| | On-going monitoring, reporting and adaptive management at site and landscape scale. | Reports and monitoring data demonstrating positive effect of on-going adaptive management at site, watershed, and landscape scales (based on metrics for Desired Conditions). | W/R |
| **Restored meadow functionality moves toward desired conditions** | Vegetation monitoring (mapping and community composition reporting). | Monitoring reports show that vegetation composition and distribution approaches conditions observed in reference meadows. | W |
| | Weed monitoring and reporting. | Monitoring reports show that invasive plant species cover remains low in restored meadows (under 5% cover). | W |
| | Aquatic habitat condition monitoring and reporting. | Monitoring reports show that aquatic habitat conditions approach those observed in reference meadows. | W |
| | Riparian and terrestrial habitat condition monitoring and reporting. | Monitoring reports show that riparian and terrestrial habitat conditions approach those observed in reference meadows. | W |
| | Focal species occupancy or population trends are evaluated relative to desired conditions. | Reports show that focal species occupancy or population trends match or approach those observed in reference meadows. | W |
| **Restored meadow functionality resilient across the range of water year types (reduced vulnerability)** | Vegetation monitoring (mapping and community composition reporting). | No state shifts in vegetation other than restoration changes; shifts may occur but overall suite of vegetation communities remain same through range of water years. | W |
| | Weed monitoring and reporting. | Non-native invasive plant species do not take hold at site (or are actively managed). | W |
| | Aquatic habitat condition monitoring and reporting. | Channel aquatic habitat conditions remain steady through range of water years and potential channel migration. | W |
| | Riparian and terrestrial habitat condition monitoring and reporting. | Meadow riparian and terrestrial habitat conditions remain high through range of water year types. | W |
| | Focal species occupancy or population trends are evaluated across many water year types. | Reports show that focal species occupancy or population trends are increasing or stable across variable climatic conditions. | W/R |
| **Benefits to diversity are achieved** | Monitoring and modeling. | Results show significant change over time at landscape scale (population recoveries?). | W/ R |
| **Benefits to hydrology are achieved** | Monitoring and modeling. | Results show significant change over time at landscape scale (increased storage, cooler temperatures and late season flows?). | W/ R |
| **Benefits to soils and carbon storage are achieved** | Monitoring and modeling. | Results and reports show significant change over time at landscape scale if such change is expected based upon outcomes of current studies. | W/ R |

Table 3. Fourth column indicates local watershed (W) or regional scale (R)

# Approach 2

## Overview

The emphasis of this approach is to improve policy, legislation, and permitting to benefit meadow health, function and resilience. The focus will be on 'golden keys' that can unlock the capacity and potential of existing institutions and resources to protect and restore meadows. This could include site visits to familiarize regulators with the sites and proposed work early in the compliance process, and/or expediting the permitting process while completing all requirements for permitting agencies. This approach also includes increasing availability of private and public sector funding to support the full meadow restoration and adaptive management process.

## Desired Outcomes, Actions and Milestones

A set of desired outcomes, necessary actions and milestones for Approach 1 are provided in Tables 1-3 below. These are presented as short-term (to occur within next five years), intermediate-term (to occur within next ten years), and long-term (to occur within the next fifteen years) actions. The fourth column indicates whether the actions are expected to occur at the local (W for watershed) or regional (R) scale. In this case, watershed refers to approximately HUC12 size watersheds or HUC10 and regional stands for the Strategy Area (Figure 2).

## Approach 2: Short-, Intermediate- and Long-term Plan

Desired outcomes, actions and milestones to enhance regulatory and institutional funding capacity and coordination.

| Desired Outcomes | Actions | Milestones | W/R |
|---|---|---|---|
| **Streamlined permitting processes** | Explore options for multiple meadow permitting such as "batch" or "programmatic" permits. | Multi-meadow permitting implemented staff time, costs, and regulatory response is tracked. | R |
| | Change in Nationwide 27 permit – Section 404 permit to allow streamlined process on federal land (to align with current private lands expeditious process). | Stream-lined Nationwide permitting allowed for meadows on federal lands. | R |
| | Clarify SWPPP and 404 permit interaction and acreage triggers, and ability of USFS personnel to complete SWPPPs. | Clear understanding amongst regulators that SWPPP applies to area above high water mark only. Clear direction for USFS staff on ability to prepare SWPPP's. | R |
| | Work with SHPO to identify how permitting can be expedited. | SHPO permitting occurs at reasonable pace and is no longer a bottleneck for restoration projects. | R |
| | WRDA wetland restoration agreement (ACE process) – Get agreement with each region of the CORPS to have a dedicated ACE person to address permits. | Identified ACE permitting person for each ACE region in state; permits are processed at reasonable pace and not a bottleneck for restoration projects. | W/ R |
| **USFS support in priority Districts obtained** | Place meadow restoration benefits at District to watershed scale. | Watershed or District level document on benefits completed. | R |
| | Align consistent NGO to provide support and communication. | NGO engaged in communication with District or Supervisors Office Specialists. | W |
| **USFS support in priority Districts obtained** | Develop strategic plan that places meadow restoration benefits in context of region and forests. | Strategic plan accepted by Region 5 Forest Service that is integrated into planning, management and monitoring process. | R |
| | Work with USFS Standards and Guides to ensure they contribute to healthy meadow soils. | USFS Standards and Guides for soils has been peer reviewed and by meadow soil scientists. | R |
| **Support/ engagement with National Park Service obtained** | Work with NPS staff to develop meadow restoration and management strategy for NPS lands. | Strategic plan accepted by NPS that is integrated into planning, management, and monitoring process. | R |
| **Consistent conservation across ownership boundaries is enabled** | Support development of Federal and private lands policy that supports species and biodiversity conservation. | Federal lands policy accepted by California regions of USFS, NPS and BLM, private lands accepted by Morgan Foundation, SPI etc. | R |
| | Local NGO(s) work with Federal land-owning agency (NPS, USFS, BLM) to help coordinate with local private landowners to restore meadows in target watersheds. | Coordinated actions and clear communication among public lands agency, private landowners, and NGO that facilitates meadow restoration, management and monitoring. | |
| **Support from key regulatory agencies obtained** | Create and refine species specific and habitat protocols that are consistent with Conservation Strategies or approved by regulatory agencies (USFWS or NOAA or State) or are from peer reviewed papers. | Protocol acceptance by agencies and published if new methodologies are developed. | R |

Table 4. Fourth column indicates local watershed (W) or regional scale (R)

## Approach 2: Short-, Intermediate- and Long-term Plan Cont.

Desired outcomes, actions and milestones to enhance regulatory and institutional funding capacity and coordination.

| Desired Outcomes | Actions | Milestones | W/R |
|---|---|---|---|
| **Beaver policy reform** | Identify policy barriers to appropriate use of beavers for maintaining and restoring meadows and streams. | Policy barriers identified and summarized in a report shared with appropriate agencies (DFW, USFS, NPS, and NRCS) and land managers (NSP, private). | R |
| | Develop strategies for desired policy reform regarding beavers. | Strategies developed and shared with the meadows partnership as a report. | R |
| **Support programs that provide funding for carbon, water and wildlife benefits from meadow restoration obtained** | Research and develop payment for ecosystem services program(s) relevant to hydrology, carbon and biodiversity. | Payment for ecosystem services program established and implemented relevant to federal, state and private lands. | R |
| | Support development Federal lands policy that rewards Carbon sequestration and other ecosystem benefit credits. | Federal lands policy accepted by California regions of USFS, NPS and BLM; funding through Carbon and other ecosystem benefit credits. | R |
| | Identify and advocate for funding programs that support meadow restoration and monitoring at federal level. | Continued or increased availability of federal funding from current or new sources. | R |
| | Identify and advocate for funding programs that support meadow restoration and monitoring at state level. | Continued or increased availability of state funding from current or new sources. | R |
| | Advocate for public funding to support planning, pre-project monitoring and permitting (since this is hardest funding to get). | Continued or increased availability of state and federal funding to do requisite planning, pre-project monitoring, and permitting. | R |
| **Support federal and state funding programs for meadow restoration obtained** | Determine degree of fit and/or alignment with private funding sources. | Identification of private funders that are aligned with meadow restoration. | R/ W |
| | Develop and implement funding from well-aligned private funding sources. | Number of meadow restoration projects supported through private funding (dollars). | R/ W |
| **Identification and access to private funding for meadow restoration addressed** | Track lessons learned in how to 'market' restoration to private sources. For example, 'save' shovel ready project costs for private funding. | Memo that is updated annually on lessons learned in accessing private funding. | R |

Table 4. Fourth column indicates local watershed (W) or regional scale (R)

# Approach 3

## Overview

The emphasis in this approach is on actions that can be taken to address institutional capacity shortfalls, build regional partnerships, and maintain a high level of communication and shared knowledge. This approach focuses on improving communication and partnering, encouraging different modelsin cooperation, education and outreach, increasing institutional capacity, and supporting diverse representation.

## Desired Outcomes, Actions and Milestones

A set of desired outcome, necessary actions and milestones to guide this approach are provided in Table 5 below. It is expected that all of these actions will begin in the short-term (to occur within five years) and extend into the intermediate-term (to occur within ten years). On-going support of smaller local partners will be required for the long-term (within next fifteen years). The fourth column indicates whether the actions are expected to occur at the local (W for watershed) or regional (R) scale.

## Approach 3: Short-, Intermediate- and Long-term Plan

Desired outcomes, actions and milestones to increase and diversify institutional and partnership capacity for meadow restoration and/or protection in the greater Sierra.

| Desired Outcomes | Actions | Milestones | W/R |
|---|---|---|---|
| **Maintain and grow open communication among institutions and individuals** | Build upon and maintain cross-institutional communication and support network for meadows. (SMRRP and beyond) | Number of institutions engaged in meadow conference calls and in annual meadow meetings. | R |
| | Build upon and maintain UC Davis Meadows Clearinghouse. | Clearing House continues to grow and provide most up to date data and reports in highly accessible way(s). | R |
| **Increase participation of private landowner in meadow projects** | Identify areas with priority meadows, where private lands dominate and where current participation is low. | Map with priority privately owned meadows identified that are in areas with low participation. | R |
| | Outreach with local institutions (RCDs, local Land Trusts and other Natural Resource Groups). | Number and geographic distribution of private land owners engaged in meadow restoration projects (landowners by county). | W |
| | Partner with local groups to train and provide initial support to get programs running. | Number of local groups engaged in meadow restoration projects (number of groups; number of meadows). | W |
| | Support nascent US Fish and Wildlife Service focus on private meadows. | Number of grants and partnerships. | R |
| **Increase the number and capacity of existing practitioners through training/ partnership** | Develop and implement training programs and partnerships for all steps in meadow restoration: applying for funds, monitoring, permitting, restoration design, restoration implementation, adaptive management. | New institutional members become self-sufficient for meadow projects. Grants are successful due to partnerships. | R |
| | Determine entities involved in meadow protection. | List of contact created and added to this partnership list. Suggestions include Native Plant Society, Cattleman's Association etc. | R/W |
| | Determine where public and private meadows that have been restored in the past or are functioning well and could need protection in the future. | Outreach to public and private meadow owners at sites of past restoration conducted to determine interest in protection options. | W/R |
| **Increase/develop resources to aid practitioners/guide through process** | Build on existing resources to provide accessible (on Meadows Clearinghouse website) guides. | Guides easily found and accessed on Meadows Clearinghouse website; frequently used and updated. | R |
| **Convene meetings** | Meadow Conference(s) to identify information gaps and to work on strategy update and creation. | Number of working partners who attend; the identification of new gaps; and updated strategies for increasing the pace and scale of restorations based on implementation of current strategy. | R |
| **Communicate benefits** | Identify benefits of restoration and determine confidence of achieving these benefits. | Consensus document on meadow benefits available. | R |
| **Integrate with Regional and State Plans** | Continue to advocate for the inclusion of meadow restoration within various plans: CA Water Plan, SNC Watershed Improvement Program, Forest Plans, ACWA Headwaters Framework, etc. | Meadow restoration highlighted in local and regional plans. | R |

Table 5. Fourth column indicates local watershed (W) or regional scale (R)

# Section VI

## Next Steps: Applying the Meadows Strategy

# Next Steps and Moving Forward

## Meadow Protection and Enjoyment

- Develop prioritization for restoration and protection white paper (brief) supported by limiting factors analyses and existing databases on distribution of rare meadow dependent species relative to the landscape or watersheds within and among land owners. Much of these databases exist and an excellent prioritization framework based on these databases was presented to the larger group at the Second Meadow Meeting in March 2016. We anticipate that this would be made available by March 2017.

- Work on a white paper (brief) to link whole watershed management including roads, trails, dispersed camping, thinning needs and other components in a watershed that can and do influence hydrology, climate stressors and risk of high intensity wildfire as they affect or are effected by meadows.

- Develop Forest Service Strategy to complement this Strategy. Much of Approaches 1- 3 cover many of the needs of the National Forests within the Strategy Area. The purpose and goals align with the Region 5 Ecological Restoration Leadership Intent (USDA Forest Service 2015).

- Pursue an NCEAS working group to build upon existing evidence of ecological, economic, and social benefits of meadow restoration. This will have the added benefit of identifying true gaps in our knowledge.

- As new topics arise, evaluate their relevance to the Strategy and apply resources to investigate and write white papers (briefs) on the issues.

- Several studies are testing new restoration methodologies. Write briefs on progress on these studies to the larger Sierra Meadows Partnership group.

- Several test cases and case studies are underway; write briefs and summarize the intent and methods to be employed.

- Characterize meadow condition / vulnerability across the Strategy Area (based on landscape data and local / project level data):
  - Articulate specific Desired Conditions for area.
  - Develop objectives to focus on function (three areas / multiple scales).
  - Identify priority meadows.
  - Apply coordinated pre and post project monitoring to measure effects.
  - Apply case study to determine if the multiple meadow project will go through compliance and permitting in an expedited way.
  - Implement.
  - Monitor, manage, report.
  - Report on Framework process and lessons learned.
  - Report on Progress made on Assessment, Permitting and Compliance and lessons learned.

# Conclusion

The Sierra Meadows Partnership has identified a purpose, a set of goals and a series of actions aimed at increasing the pace, scale and efficacy of meadow restoration.

The three approaches to meadow restoration described in this paper address not only how to make positive change with respect to “on-the-ground” restoration, but also institutional change in terms of permitting, planning, funding and stakeholder involvement and partnership capacity. To achieve the target of restoring and protecting 30,000 acres in a 15 year period will require an all-hands, all-lands approach involving people, institutional change, improved coordination as well as perseverance.

The Strategy is intentionally ambitious. However, the Sierra Meadows Partnership, with this body of work, are poised for such an ambitious challenge. We, with the support of all, look forward to its implementation.

# Section VII

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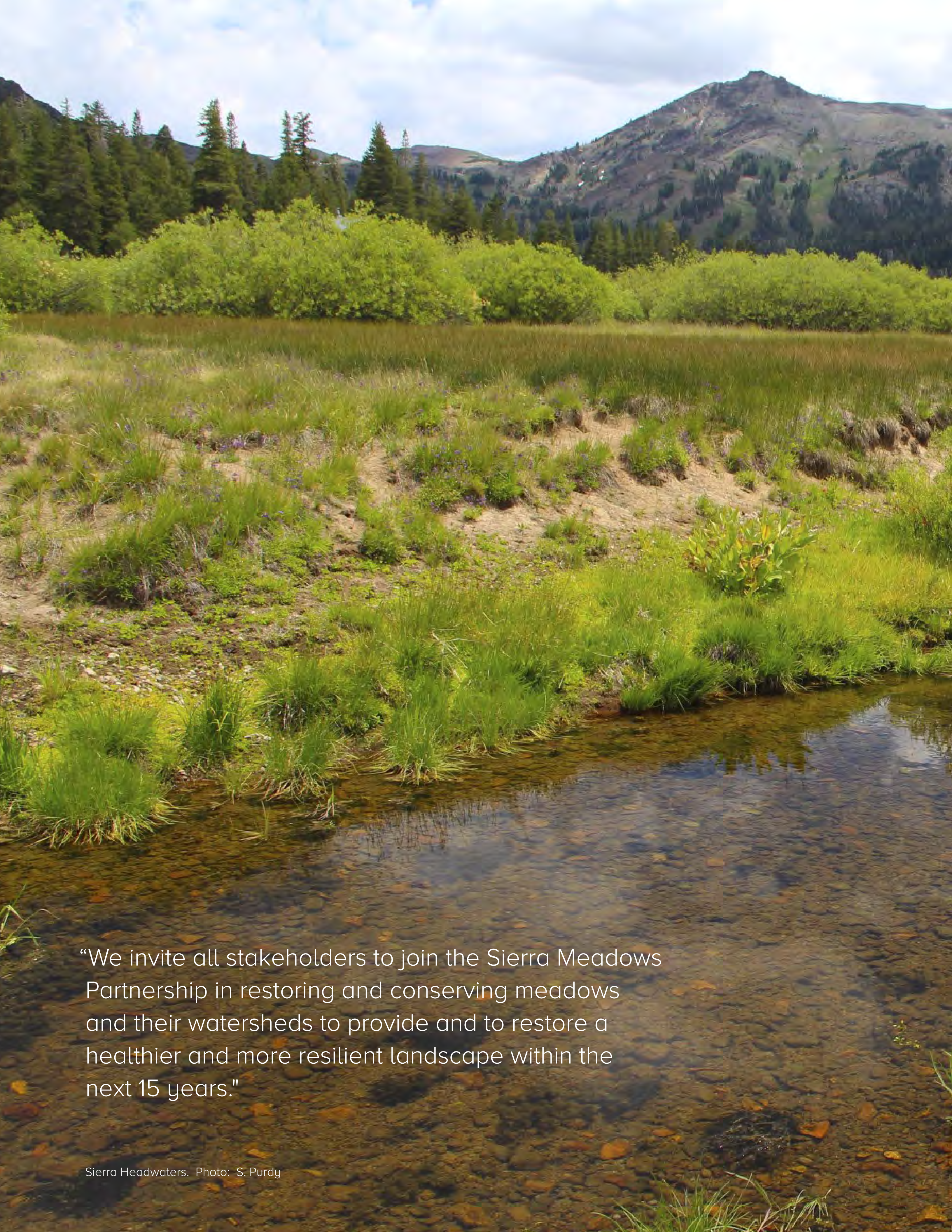

“We invite all stakeholders to join the Sierra Meadows Partnership in restoring and conserving meadows and their watersheds to provide and to restore a healthier and more resilient landscape within the next 15 years."

Sierra Headwaters. Photo: S. Purdy

The Sierra
Meadows
Partnership

Collaborative meadow
restoration and protection.