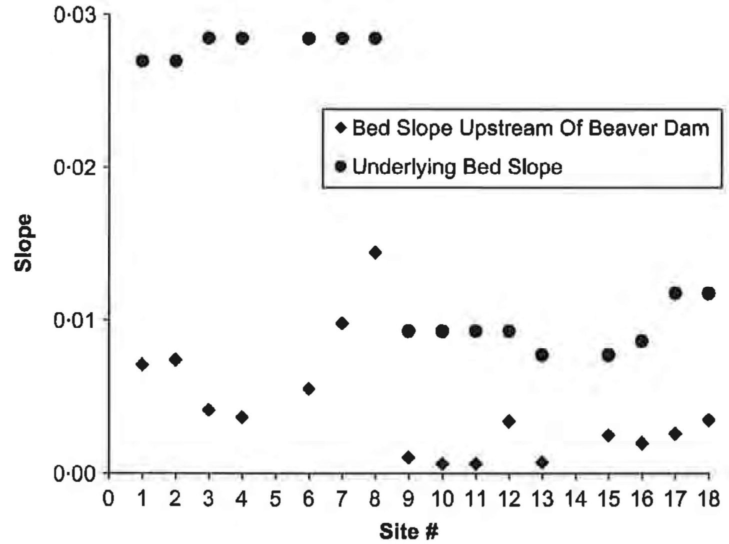

Figure 5. The accumulation of sediment behind beaver dams consistently lowered the slope of the stream bed. Upstream of beaver dams, bed slopes averaged 0·004, while the underlying bed slopes averaged 0·018. Circles mark the underlying bed slope; diamonds mark the bed slope immediately upstream of the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

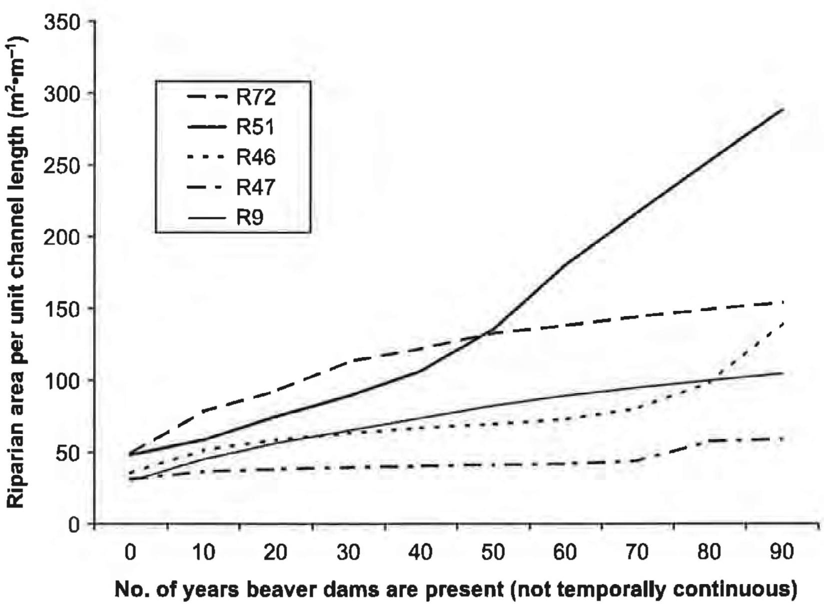

Figure 6. Estimated increase in stream-adjacent area within 0·5 m of the channel bed (i.e. the riparian area) as a function of the number of years for which the reach has active beaver dams, for five reaches on Bridge Creek that currently contain beaver dams. An aggradation rate of 0·05 m for each year 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.

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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.

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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

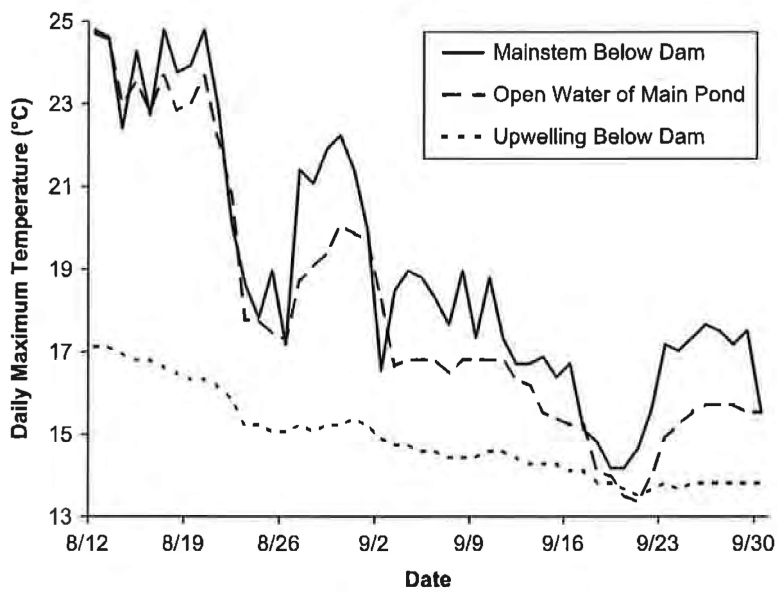

Figure 8. Temperature profiles of lower Bridge Creek in late summer 2005, showing that relatively cool pockets of water with mild temperature fluctuations exist below beaver dams, presumably the result of accumulated pond water above the dams downwelling through the alluvium and then upwelling below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

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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

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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.

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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.”